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Performance Characteristics of Lithium-Ion Cells for Mars Sample Return Athena Rover

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ABSTRACT

Future planetary exploration missions, especially Landers and Rovers, will utilize lithium ion rechargeable batteries, due to their advantages of reduced mass and volume compared with non-lithium systems. In addition to the usual requirements of high specific energy and energy density, some applications, e.g., Mars Landers and Rovers, require the batteries to be functional over wide range of temperatures, i.e., -20 to +40°C. Several prototypes with modified chemistries commensurate with these mission needs were built by U.S. battery manufacturers, in conjunction with a NASA-DoD Interagency developmental effort and are being tested at JPL in the last couple of years. The proposed Mars Rover will have three lithium ion batteries (with one serving the purpose of redundancy) connected in parallel, each with four 6-9 Ah cells in series, to augment the solar array. The charger for these Rover batteries is being designed and built in-house. In this paper, we will present several performance characterization tests, including cycle life at different temperatures, rate capability at various charge/discharge rates and temperatures and real time and accelerated storage, which were carried out on these prototype cells in support of the Mars exploration missions.

INTRODUCTION

Mission Objectives

NASA is undertaking a detailed exploration of the planet Mars with the use of several robotic spacecraft including Orbiters, Landers, Rovers, Scouts and Microprobes. Following the recent set backs of two Mars missions, there have been some delays and even cancellations of some of the proposed missions in the immediate future, i.e., 2001 Mars Sample Return Lander and 2003 Mars Rover missions. The entire Mars Exploration architecture is currently being reviewed to formulate new, robust missions. The scientific goal of these missions, however, remains the same, i.e., to determine the geologic and climatic history of a site in the ancient highlands of Mars with conditions supposedly favorable to the preservation of evidence of possible prebiotic or biotic processes. Specific objectives of these missions would thus include 1) taking color stereo images of the Martian surface, 2) determining the elemental and mineralogical compositions of Martian rocks and soil to derive information of their geology and climate, 3) obtaining microscopic images of the rocks and soils and 4) finding and collecting the samples most likely to preserve the evidence of ancient environmental conditions and possible life and storing them for return to Earth. The early missions will cater to *in-situ* analysis of Martian samples, whereas the latter sample return missions will focus on bringing the Martian samples back to the Earth. Typical payload elements in such sample return Rovers/Landers would include Pancams for color stereo imaging, an $\propto$- proton X-ray spectrometer for elemental composition analyses, Mossbauer, Mine-TES and Raman spectrometers for mineralogical composition analyses, a microscopic imager for close-up imaging and a mini-corer and sample container for sample collection and storage.

Li Ion Rechargeable Batteries for Mars Rover

The main power source for the Mars (2003) Rover consists of a Ga-As solar cell array. The auxiliary power source provides power for the nighttime and peak power operations is a lithium ion rechargeable battery. The lithium ion rechargeable battery for the proposed Rover will have 16 V and 150 Wh, with the total mass and volume of the battery not exceeding 3 kg and 2 liters, respectively. Three four-cell (each of 6-7Ah) strings will be connected in parallel with a diode protection, with one string providing some redundancy. Presently, the design of the battery is compatible with either prismatic or cylindrical cells. The above-specified energy of 150 Wh is to be made available after about two years of activation, with the preferred mode of storage during flight integration and cruise being the battery off the buss and at a temperature of 0-10°C. One critical performance requirement for the battery is the need for it to operate at sub-zero temperatures at moderate rates (maximum of C/2), without any reduction in the room temperature performance. The batteries will be provided with a heater to maintain temperatures of at least -20°C (minimum). Charging of the cells will be carried out at relatively higher temperatures (0 to +30°C). The battery will be charged with an indigenously built charge control unit, which facilitates individual cell monitoring and cell balancing. A cycle life of over 200 cycles (to 80% of initial capacity) and two years of calendar life are required for the mission.

Earlier, we have briefly reported the performance characterization tests carried out on prototype lithium ion cells, fabricated by different manufacturers under a NASA/DoD lithium ion battery consortium.[1-5] Under this program, multiple manufacturers are being supported to provide the desired technological developments and their cells, either prismatic or cylindrical and with capacities ranging from 4 to 40 Ah, are being evaluated at JPL under generic performance conditions as well as those relevant to Mars Exploration programs (Landers and Rovers). In this paper, we provide the updates of such performance characterization tests on 4 - 9 Ah lithium ion cells, specifically for the applications similar to Mars Rovers. Similar tests carried out on larger cells (20 Ah) for Lander applications are being communicated in our companion paper.[6]

Li ION CELLS EVALUATION

The lithium ion cells evaluated contain proprietary electrolytes, electrode materials and designs to achieve the desired performance characteristics, i.e., low temperature performance and cycle life. It was deemed essential to keep the manufacturers anonymous in this paper to promote parallel development at each of the respective organizations. All the cells have gone through a series of tests, aimed at establishing the baseline performance data of all the cells and validating lithium ion technology for the intended missions. Accordingly, these tests consist of both generic performance tests and mission specific tests. The generic tests include cycle life at 100% DOD at three different temperatures of 25, 40 and -20°C, and rate characterization at different rates of charge and discharge (typically C, C/2, C/3, C/5 and C/10) and temperatures (40, 25, 0 and –20°C). The mission specific tests include cycling alternating high and low temperatures, and accelerated and real-time storage under conditions similar to spacecraft cruise. In addition, several miscellaneous tests have been carried out to understand the thermal characteristics, temperature-compensated voltage charging, and failure modes.

STATUS OF LITHIUM ION CELLS FOR ROVER APPLICATIONS

Cycle Life

Fig.1 displays the cycle life characteristics of various lithium ion prototype cells at 25°C. The data include cells from three different sources are comprised of four different designs, and are configured either in the prismatic or cylindrical shape and have initial capacities ranging from 4-9 Ah. The cycling regime typically consists of a charge at a C/5 rate (based on the observed capacity) to a charge cut-off voltage of 4.1, followed by tapered charging at the same voltage to C/50, or for an additional three hours (usually the current limit is approached earlier than the time limit), and a discharge at C/5 to 3.0 V, with a rest period of fifteen minutes between charge and discharge.

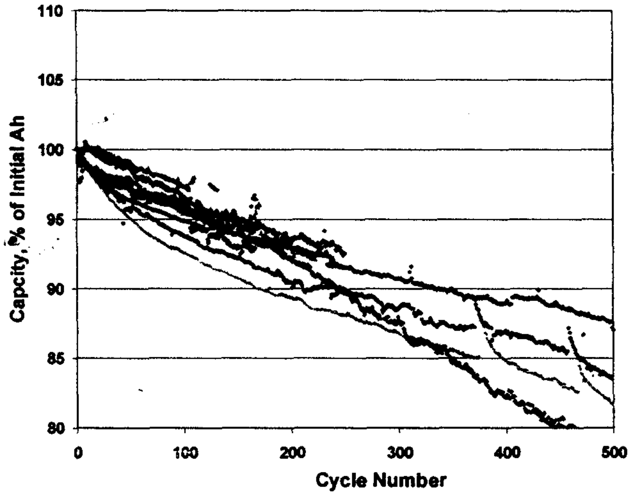

Fig. 1 Cycle life of Li ion cells (4-7 Ah) cells at 25°C for Mars Rover applications.

As may be seen from Fig. 1, the cycle life of the cells is generally acceptable from the mission point of view, with over 80% of the initial capacity being retained over 500 cycles. There is also noticeable spread in the capacity fade rate in the above cells from different manufacturers, stemming partly from the electrolytes (low temperature), the electrode materials and partly from the design parameters.

The cycle life characteristics of these cells at low temperatures (-20oC) are illustrated in Fig. 2. The cycling regime for these tests is similar to that at ambient temperature, except that the charge rates are reduced from C/5 to C/10, to avoid the possibility of lithium plating at low temperatures, parallel to lithium intercalation process.

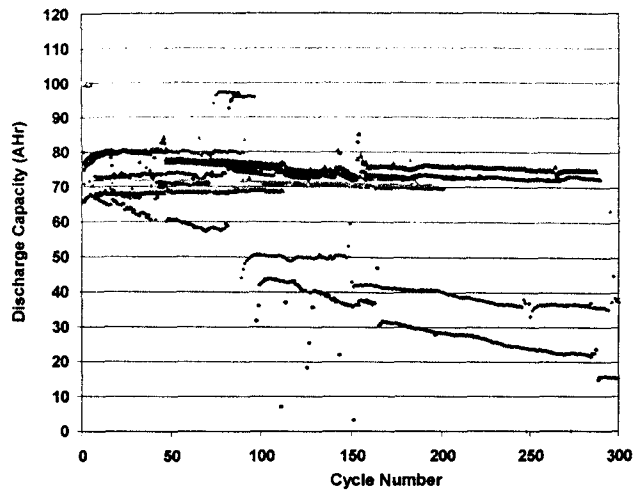

Fig. 2 Cycle life of Li ion cells (4-7 Ah) cells at –20°C for Mars Rover applications.

As may been from Fig. 2, the initial capacity at –20°C is around 70-80% of the room temperature capacity, which is quite impressive. This may be attributed to the improvements made at JPL[7] and elesewhere[8] in terms of developing low temperature electrolytes for Li ion batteries. The capacity fade rate during cycling at the low temperature is also fairly impressive, at least in most cases. However, in one set of samples, we have observed an unusually rapid capacity fade, which may be attributed to an improper cell fabrication and to the failure of the test chamber resulting in a higher cell temperatures of ~25°C.

We have seen other instances also where such occasional exposure to high temperature has become detrimental to subsequent low temperature performance. The low temperature performance is rather sensitive to any prior exposure of the cell to higher temperatures. This may be relevant to the Mars Rover missions where the battery temperature alternates between ambient and low temperatures each cycle (each day). Typically the charge temperatures are higher compared to the discharge temperature. In order to understand the capacity degradation under such conditions, We have therefore been carrying variable temperature cycling tests, where the cell is cycled at low (-20°C) and high (either ambient or 40°C) temperature for ten cycles alternately. Figure 3 shows typical performance under such variable temperature cycling.

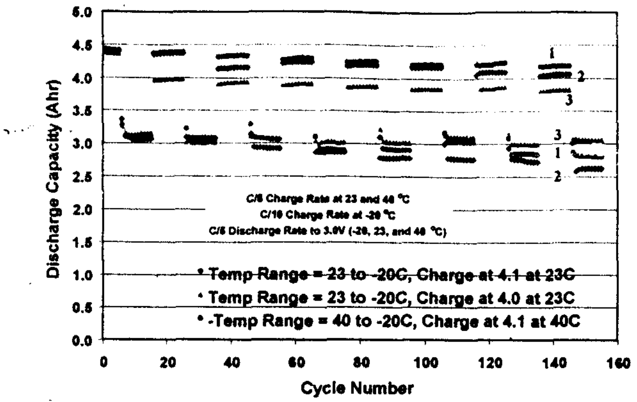

Fig. 3: Capacities of Li ion 'D' cells during cycling between –20°C and 1&3) 23°C (40°C in the case of 2) and with a charge voltage of 1& 2) 4.1 V and 3) 4.0 V.

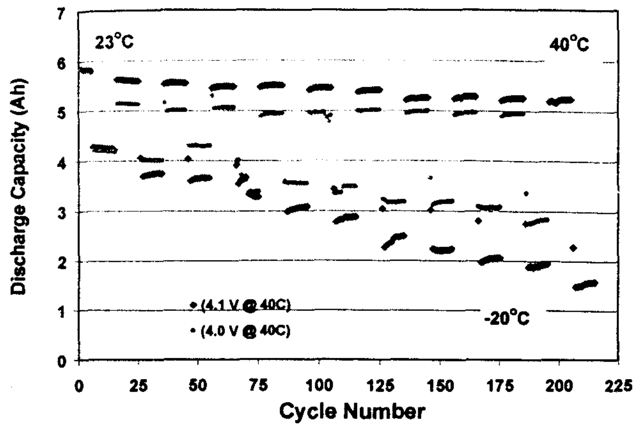

Fig. 4: Capacities of Li ion cells during cycling between -20°C and 40°C with a charge voltage of 4.1 and 4.0 V.

Fig. 3 illustrates cycling of lithium ion cells under three different conditions, i.e., cell charged to 4.1 V or 4.0 V and the cell temperature alternating between –20°C and 23°C or –20°C and 40°C. The charge cut off voltage has been reduced to 4.0 to minimize the effects of electrolyte oxidation at high charge voltages, especially at high temperatures. Another variation could be to switch the cells from low to high temperature in the discharged state, which was not pursued here. As shown in the figure, the cell capacity at the high temperature (25 or 40°C) is largely unaffected, except when the charge voltage is reduced to 4.0 V. The capacity at low temperature, on the other hand, fades at relatively rapid rate. The capacity fade at low temperature decreases with a decrease in the temperature on the high end and with a decrease in the charge voltage.

Similar measurements made with another type of cells are consistent with these observations (Fig. 4). The capacity fade is slightly higher than in Fig. 3 and also the effect of lower charge voltage on the capacity fade is more prominent.

The rapid buildup of the surface films on the carbon anode and metal oxide cathode during ambient or high temperature cycling may be responsible for the subsequently poor low temperature performance. This is evident from the Electrochemical Impedance Spectroscopy measurements on these cells (Fig. 5).

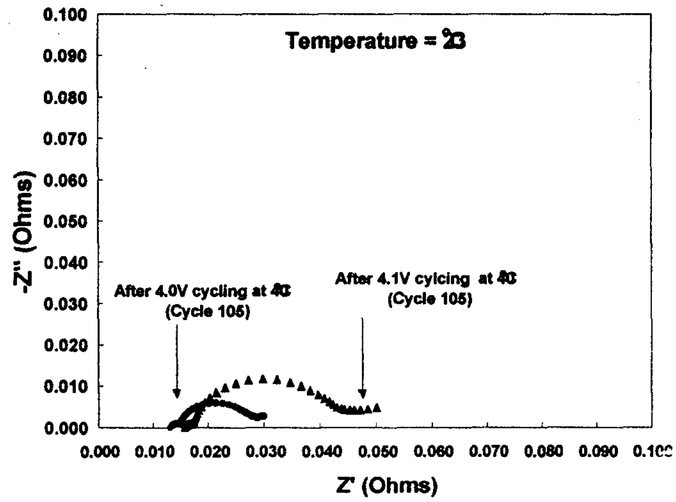

Fig. 5: Electrochemical Impedance Spectra (EIS) of Li ion cells during variable temperature cycling.

The impedance pattern of lithium ion cells is generally characterized by two relaxation loops, corresponding to each of the electrodes. Based on a comparison with the EIS response in three electrode cells, we may correlate the first relaxation (high frequency loop with the anode and the second relaxation loop with the anode. It also clear from our earlier three electrode studies on Li ion prototype cells that the surface films (SEI) on both the carbon anode as well as the metal oxide cathode build up during storage at high temperature. Likewise, there is a build up of both the relaxation loops here during the variable temperature cycling in all cases. However, the increase in the impedance is relatively small in the cell charged only to 4.0 V, compared to the cell charged to 4.1 V. It is reasonable to infer that the electrolyte-related processes corresponding to the SEI build up are potential dependent and are reduced with lower electrode potentials at cathode and higher potentials at the anode.

During the cycling, the charge to discharge capacity (C/D) ratio remains the same; in fact it gets closer to unity in the course of cycling. However, the round trip energy efficiency decreases during cycling, as illustrated by the typical data from one set of prototype cells in Fig. 6.

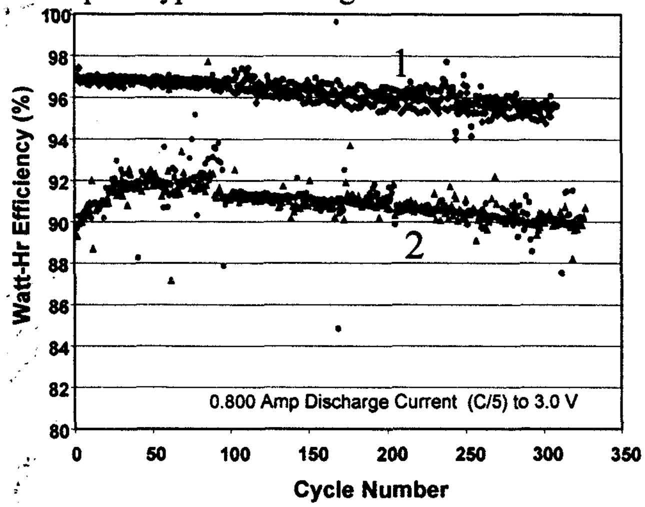

Fig. 6: Round trip energy efficiency of lithium ion cells during 100% DoD cycling at 1) 25 and 2) – 20°C.

As may be seen from the figure, the Wh efficiency is typically around 97 % a for a cell of about 9 Ah, which implies that about 3 % of the energy is being lost in the form of resistive heating. At low temperatures, the corresponding numbers are much higher (about 8% going for the resistive heating) due to increased cell internal resistance at low temperatures. In both cases, i.e., cycling at ambient as well as low temperatures, the energy efficiency tends to decrease with cycling and a value slightly higher than unity.

Performance Characterization : Different Rates and Temperatures

As mentioned above, one critical aspect of the Mars Lander and Rover missions is the low temperature performance, i.e., at –20°C and at moderate rates of C/5 as mentioned above. All the types of cells, have, therefore been subjected to a series of charge and discharge capacity measurements at different rates and different temperatures. The cells were examined for their rate capability during discharge as well as charge at different temperatures. The rates included C/10, C/5, C/2 and C both for charge and discharge and the discharge tests were preceded by charge under standard conditions of C/10 charge and the charge experiments were followed by discharges at C/10. The temperature range included –30 to + 40°C, specifically –30, -20, 0, 25 and 40°C. These studies are mainly to assess the applicability of these cells for the MSR Athena Rover applications. From these tests it became clear that the cells are rather sensitive to the history, i.e., the extent of cycling and the conditions experienced prior to the test. In particular, the low temperature performance is different for the pristine cells compared to the cells cycled through characterization tests from the high end of the temperatures (25 and 40oC). This is very similar to variable temperature cycling described above. Fig. 7 shows the variation of discharge capacity of Li ion cells from one manufacturer as a function of rate and temperature.

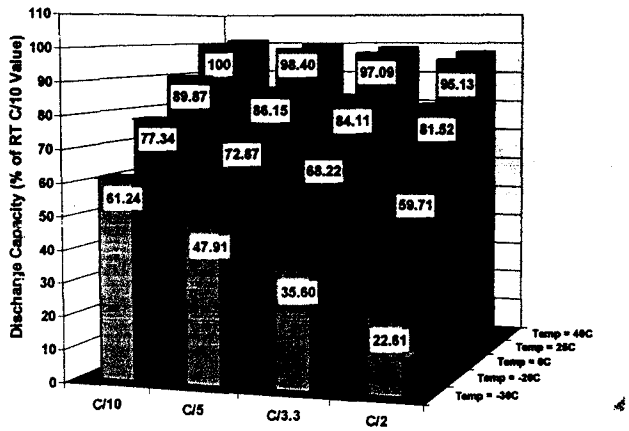

Fig. 7 : Discharge capacity as a function of rate and temperature of Li ion cell for Mars Rover.

The above data correspond to one type of lithium ion cell, which is typical of the cells containing modified cell designs, though other cells also showed capacities in the same range as a function of temperature. As shown in figure 5, Li ion cells can provide a high proportion (over 70% of RT capacity) at –20°C at moderate rates of C/5, a critical requirement for the Mars Rover missions. In order to achieve such high yields at low temperature, with the preceding charges carried out at the low temperatures, several modification have been made to the chemistries, mainly with respect to the electrolyte. Fig. 8 illustrates the typical performance of these cells at various rates at low temperature of –20°C, in the form of discharge curves.

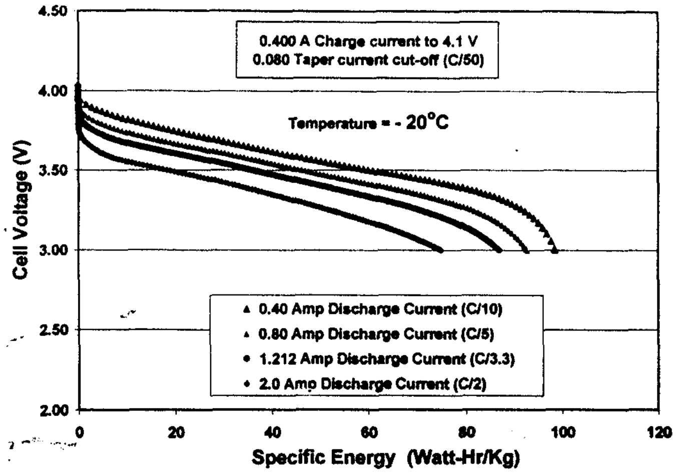

Fig. 8 : Discharge curves of lithium ion cells at discharge rates of and at a low temperature of -20°C for MSR Athena Rover applications.

The cells have shown impressive specific energies of ~ 130-140 Wh/kg at ambient temperatures. More importantly, the specific energies at low temperatures relevant to Mars Lander and Rover missions, i.e., at -20°C are equally impressive, ranging for 90 –100 Wh/kg at discharge rates. Also, the cells do function at even lower temperatures of ~-30°C, albeit at low discharge rates.

Charge characteristics

Though the batteries experience slightly warmer temperatures during charge, it was deemed necessary for the Mars mission that the cell are capable of accepting charge at low temperatures. Fig. 7 shows charge profiles of one type of prototype Li ion cell with low temperature electrolyte.

As may be seen from the figure, the cells can be charged at moderate to high rates of C/2, even at low temperature. During such rapid charging, more than 70% of the capacity is accepted in the constant current mode. It is also important to note that even at low rates of charging, and even after extended periods of charging, the charge capacity would not exceed ~ 80% of the cell (room temperature) capacity. It is probably necessary to increase the charge voltages at low temperatures, at least to the extent of compensating for the ohmic polarization, which is rather significant at low temperatures.

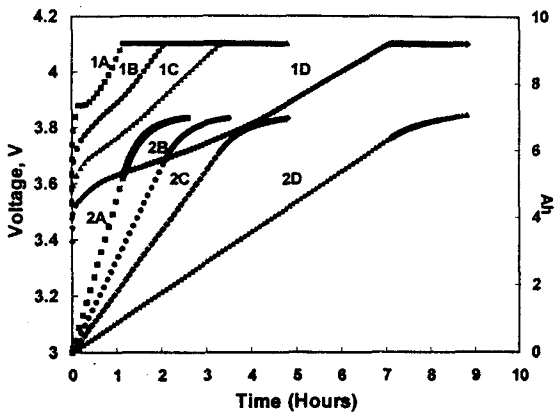

Fig. 9: Charge characteristics, i.e., 1) Voltage and 2) Capacity of Li ion cells at low temperature (-20°C) at different rates of A) C/2, B) C/3, C) C/5 and D) C/10, respectively.

EIS during cycling

We have reported in our earlier publications that the cell impedance increases during cycling. In order to monitor such changes in the cell impedance, we routinely measure the electrochemical impedance periodically during cycling (after each 100 cycles). Fig. 6 shows the typical EIS (Electrochemical Impedance Spectroscopy) plots during cycling of lithium ion cells.

As may be seen from the figure, the impedance of the Li ion cell increases appreciably during cycling. There is a small increase in the series (Ohmic) resistance but a relatively larger increase in the relaxation loop, especially the second one. From the half-cell studies on individual electrodes, we typically observe two relation loops, the high frequency loop corresponding to the surface films (SEI or solid electrolyte interface) and the low frequency loop attributable to the charge transfer process. Similar measurements in a three-electrode cell reveal that that the high frequency loop is primarily related to the processes of the graphite anode and the low frequency loop corresponds to the processes at the cathode.

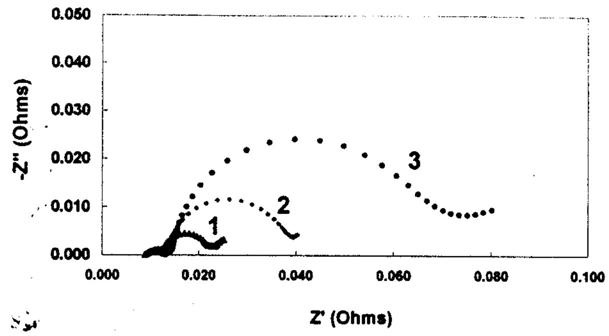

Fig. 10 EIS plots of Li ion cells after 1) 5, 2) 100 and 3) 200 cycles at 25°C.

Based on the above discussion, the above increase in the cell impedance upon cycling may be ascribed to the cathode.

Storageability of Li ion cells

The missions to Mars have typical cruise times of 7-12 months. This combined with pre-cruise storage requires that the batteries have a calendar life of at least 2 years. Subsequent to the two years storage, the cells need to perform well at low temperatures, with moderate cycling. The expected mode of storage could either be in an open circuit condition as for the Rover or on float, as required by the Lander. From our earlier studies on Lander cells, we have observed beneficial effects of storing at low temperature, at low state of charge and in float condition.

Similar studies have also been made on several smaller cells. Table 1 shows such storage data at two different temperatures and two different states of charge under open circuit conditions. As a result of the storage, the cells experience some permanent loss in the capacity, mainly as a result of increased cell impedance, which is a concern to the project. As shown in the Table 1, the permanent capacity is higher at high storage temperature, and high state of charge. The capacity loss ranges from a maximum of 8 % at 100% state of charge and 40°C to a minimum of 0.1 % at 50% state of charge and 0°C, respectively.

Table 1: Capacity of Li ion cells after storage for eight weeks

State of Charge	Temperature of Storage	Storage Time (Months)	Reversible Capacity (%)	Stored Capacity Loss (%)
50%	0°C	2	99.9	0.4
100%	0°C	2	97.5	7.88
50%	40°C	2	97.3	13
100%	40°C	2	92.9	13.3

We have continued storage test on these cells at 100% state of charge and 0°C conditions. The changes in the cell capacity since the cell fabrication are illustrated in Fig. 10. As may be seen from the figure, the cells have excellent storageability, which bodes well for many applications that would require long calendar life from the cells.

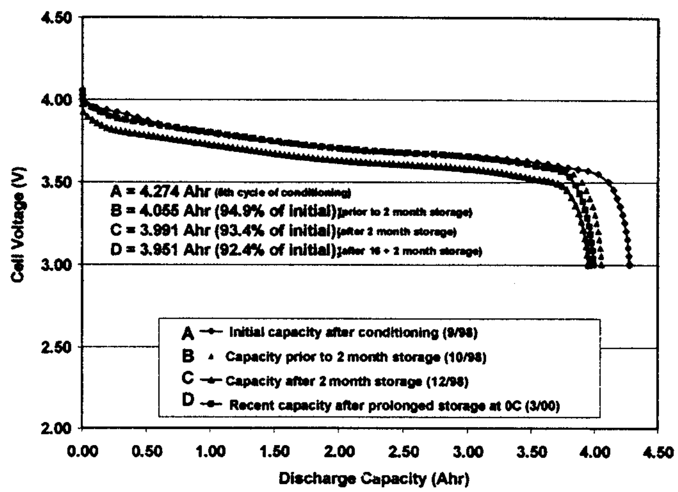

Fig. 11: Discharge curves of lithium ion cell at various stages of storage.

Charge Voltages at different temperatures

The nickel rechargeable systems, both Ni-Cd and Ni-H_2 undergo thermal runaway, when similar charge cutoff voltages are used across all temperatures. Since the cell thermodynamic potential decreases at high temperatures and the current efficiency for the parasitic oxygen evolution reaction increases at high temperatures, a lower charge voltage, termed as temperature compensated voltage (V_T) is used as a charge cut off to avoid any thermal runaway. In order to understand how the charge voltages need to be adjusted for lithium ion cells, we have generated coulometric titration curves, i.e., cell open circuit voltage as a function of state of charge at different temperatures .

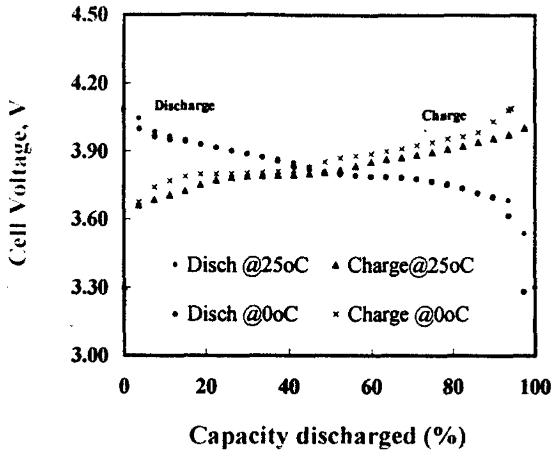

Fig. 12: OCV vs. state of charge for lithium ion cells at 25 and 0°C, during charge and discharge.

Two noteworthy points emerge from the above figure. Firstly, the OCV of a lithium ion cells does not seem to be a strong function of temperature as in the case of nickel systems. Secondly, there is no hysteresis in the charge and discharge potentials, as is typically observed with nickel systems. These, combined with the absence of a parasitic reaction as the oxygen evolution for nickel electrode, imply that the charge voltage may be compensated with temperature only based on kinetic considerations

ACKNOWLEDGEMENT

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35th IECEC, Los Vegas, NV., July 23-28, 2000

2003 MSR Athena Rover

Mission Objectives

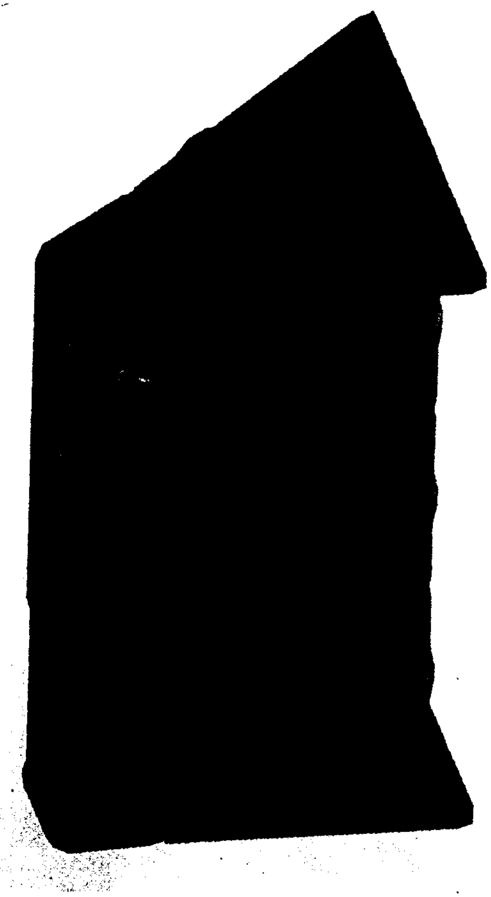
To determine the geologic and climatic history of Martian site with conditions favorable to possible life

- **Specific objective include**
  - **taking color stereo images of the Martian surface**
  - **determining elemental and mineralogical compositions**
  - **obtaining microscopic images of rocks**
  - **Collecting samples with evidence of ancient environmental conditions and possible life**
- **Payloads Elements**
  - **Pancam for stereo imaging**
  - **alpha proton X-ray spectrometer**
  - **Mossbauer, Mine TES and Raman spectrometers for mineralogical composition**
  - **microscopic imager and**
  - **mini-corer**

2003 MSR Athena Rover

Power Subsystem

- **Primary Source : Ga-As solar array**
- **Auxiliary Power Sources : Li ion Battery**
- **Li Ion Battery Characteristics**
  - 16 V, 150 Wh
  - Mass 3 kg (max) and Volume 2 lit (max)
  - Three (N+1) parallel batteries of four cells each
  - EOL (200 cycles) performance
    - 5 Ah @ 0oC at C/2
    - 3.5 Ah @ -20oC at C/2
  - Calendar life : 2 years
  - Cylindrical or prismatic
  - In-house charger
    - individual cell monitoring and cell balancing



Battery Challenges

- ***High specific Energy (Wh/kg and Wh/l)***
- ***Low Temperature Performance***
  - **Op. Temperature : -20 to +40°C**
  - **Capacity of 5 Ah 0°C at C/5 and 3.5 Ah @C/2 and -20 °C**
- ***Good Cycle Life***
  - **200 Cycles**
- ***Long Calendar Life***
  - **Two years of storage (1 year cruise) before battery operation**
  - **Low temperature performance after storage (final phase of the mission)**

NASA-DOD Interagency Li Ion Program

Objectives

- DEVELOP HIGH SPECIFIC ENERGY AND LONG CYCLE LIFE Li -ION BATTERIES
- ESTABLISH U.S. PRODUCTION SOURCES
- DEMONSTRATE TECHNOLOGY READINESS
  - LANDERS BY 2001
  - ROVERS BY2003
  - GEO MISSIONS BY 2003
  - AVIATION/UAV's BY 2001
  - MILITARY TERRESTRIAL APPLNS's BY 2001
  - LEO MISSIONS BY 2003

Technology Drivers

Mission	Technology Driver
Lander Rover	Low Temperature Operation High rate Pulse Capability
GEO S/C	10-20 Year Operating life Large Capacity cells (50-200 Ah)
LEO PlanetaryS/C	Long Cycle life(30,000) Medium Capacity Cells (50 Ah)
Aircraft	Low temperature Operation High Voltage Batteries (270 V)
UAV	Large Capacity cells (200 Ah) High Voltage Batteries (100V)

Lithium-Ion Cells for 2003 MSR Athena Rover

Program Objectives

- **Assess viability of using lithium-ion technology for future Aerospace applications.**

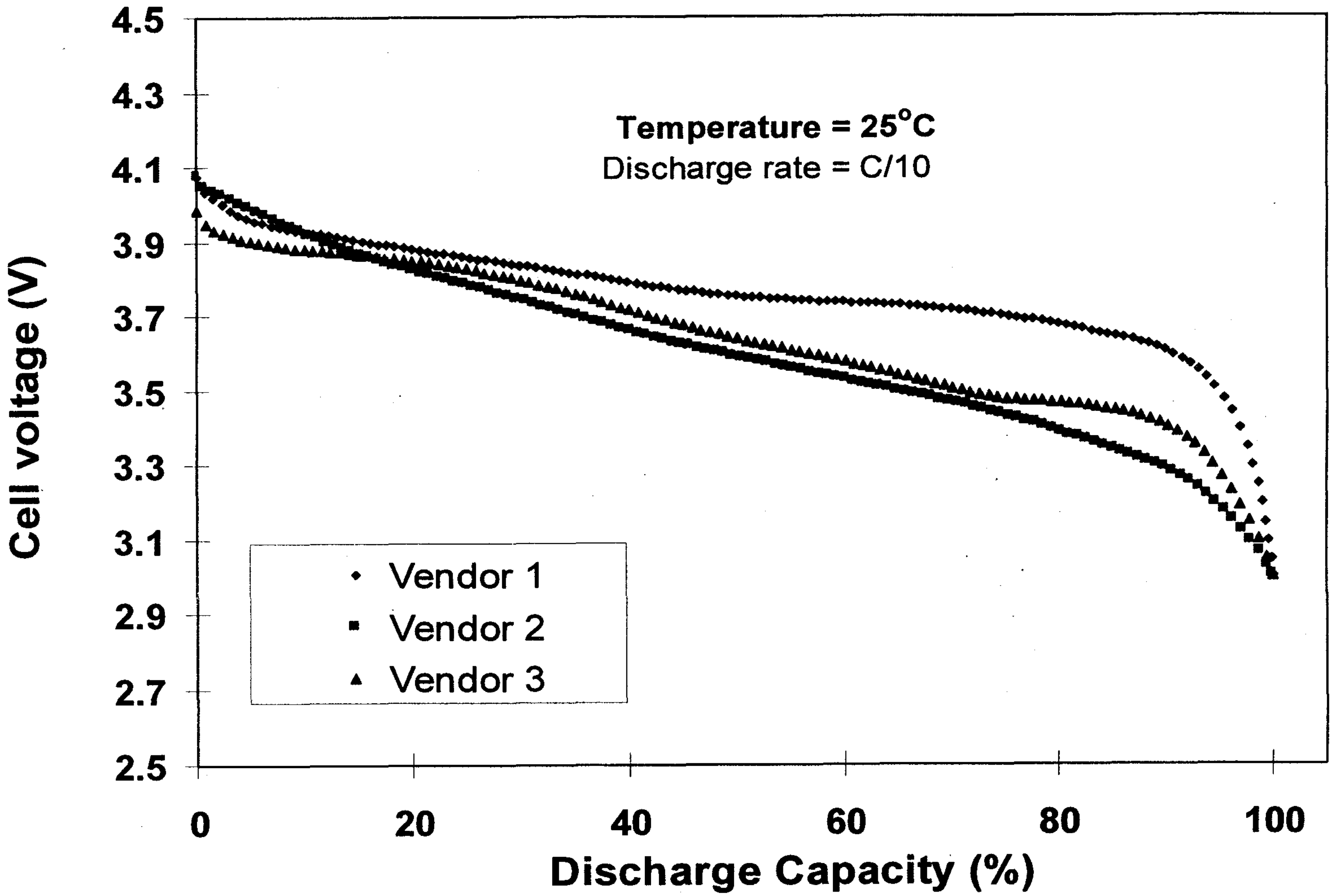
- **Demonstrate applicability of using lithium-ion technology for future 2003 Mars Sample Return Athena Rover applications.**

Lithium-Ion Cells for 2003 MSR Athena Rover

Evaluation Tests On-Going at JPL

- Cycle life performance at room temperature (25°C)
- Cycle life performance at low temperature (-20°C)
- Cycle life at alternating temperatures (40 and -20°C)
- Discharge rate characterization (at 40, 25, 0, and -20°C)
- Charge rate characterization (at 40, 25, 0, and -20°C)
- Capacity retention
- Storage characterization tests (cruise conditions)
- VT charge characterization tests
- Electrical characterization by a.c. impedance
- Thermal characterization

Lithium-Ion Cells for 2003 MSR Athena Rover
Room Temperature Discharge Characteristics



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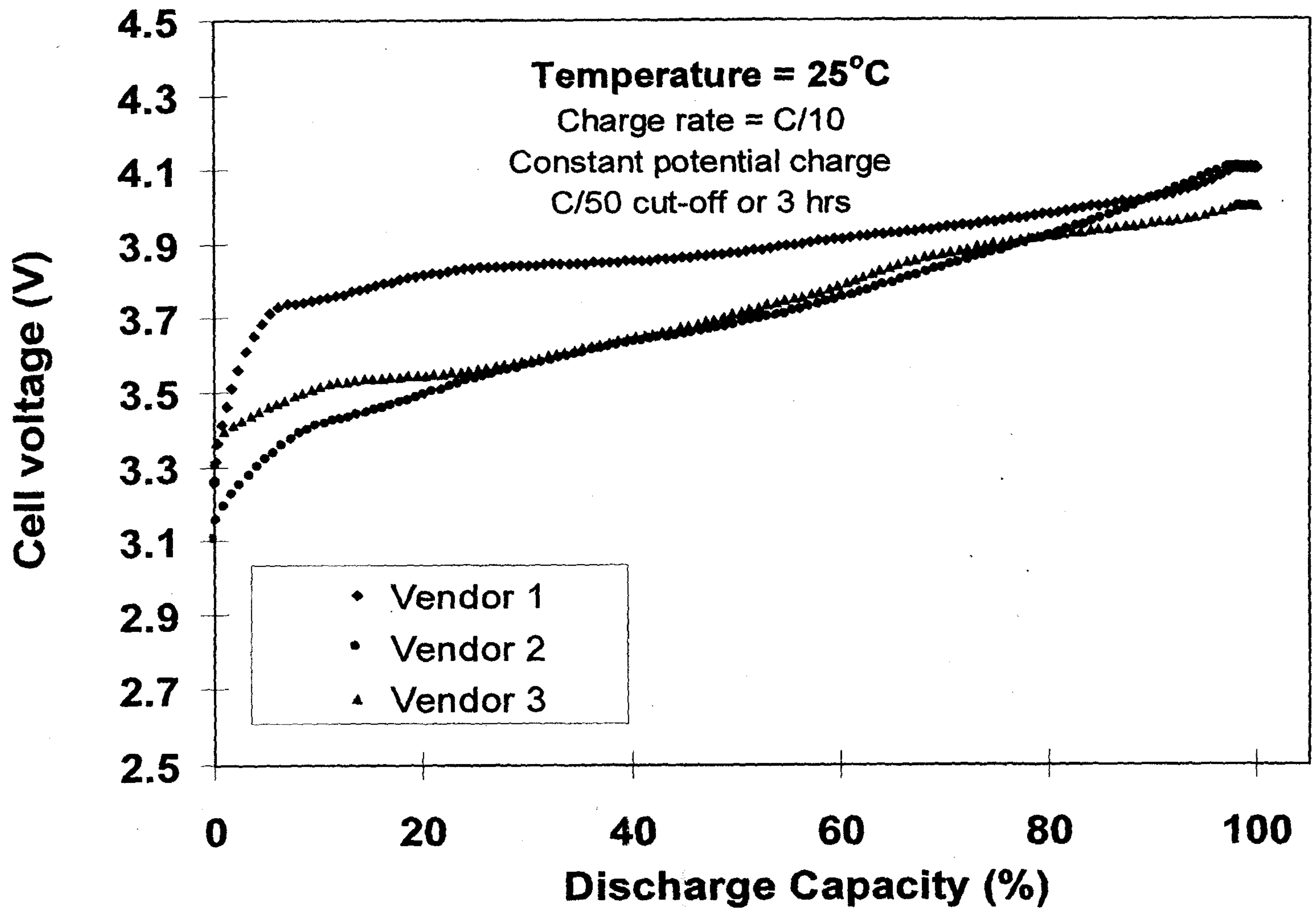
Room Temperature Charge Characteristics



Lithium-Ion Cells for 2003 MSR Athena Rover

Cycle Life Performance Tests

Requirement **: Deliver > 200 cycles on surface of Mars**

- **100% DOD cycling (3.0-4.1V, C/5-C/10)**
- **Wide temperature range (-20°C to 40°C)**
- **At end of life should deliver 5 Ah @ 0°C**

Approach**:**

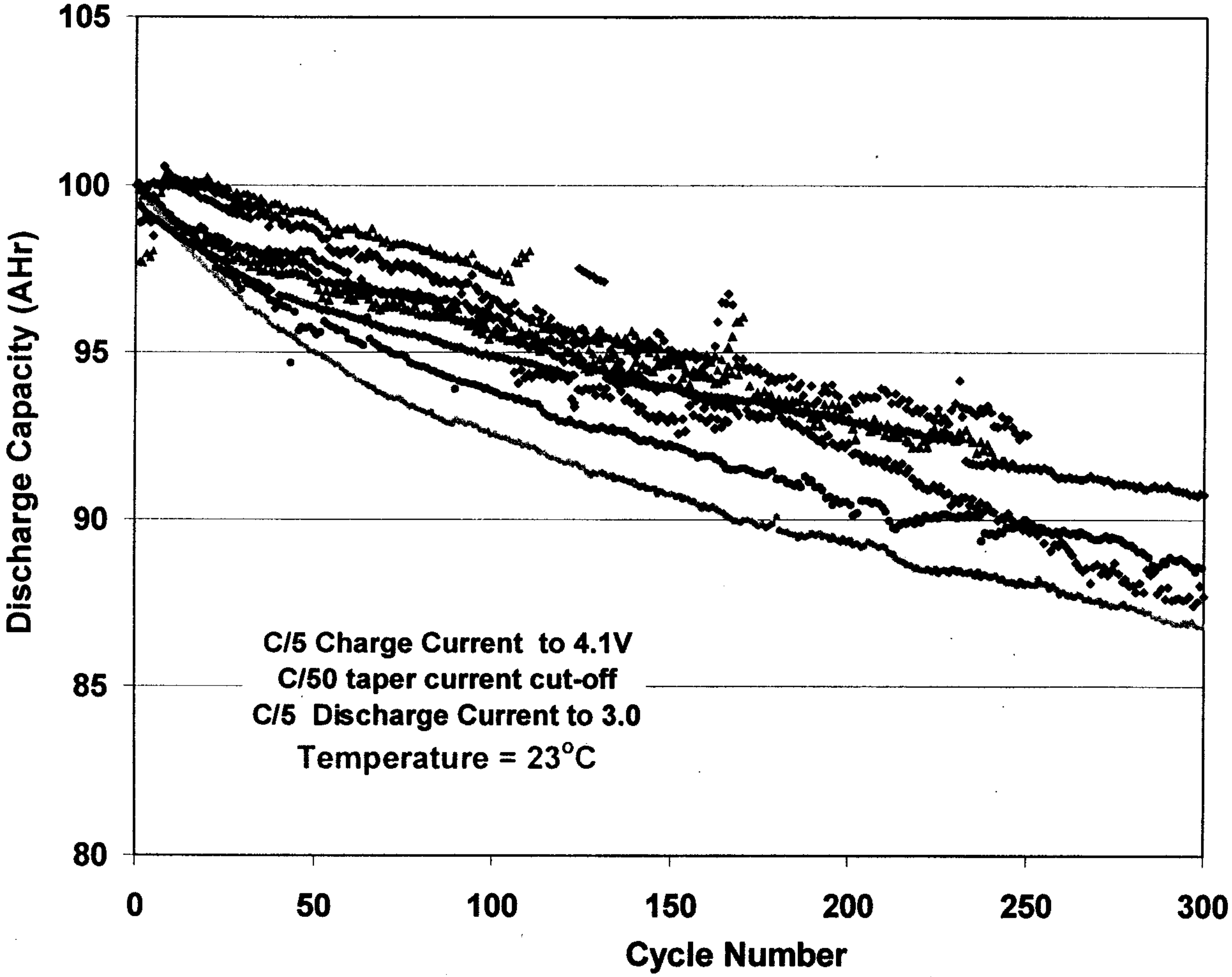
100 % DOD cycling @ 23°C (C/5 charge, C/5 discharge)
100 % DOD cycling @ -20°C (C/10 charge, C/5 discharge.)
100 % DOD cycling @ 40°C (C/5 charge, C/5 discharge)
Variable temperature cycling (temperature extremes)
Mission simulation cycling

Possible Evaluation Criteria**:**

Initial capacity (must exceed 5 Ah)
Capacity after 200 cycles (Ah)
Capacity fade rates
Capacity delivered over range of temperatures

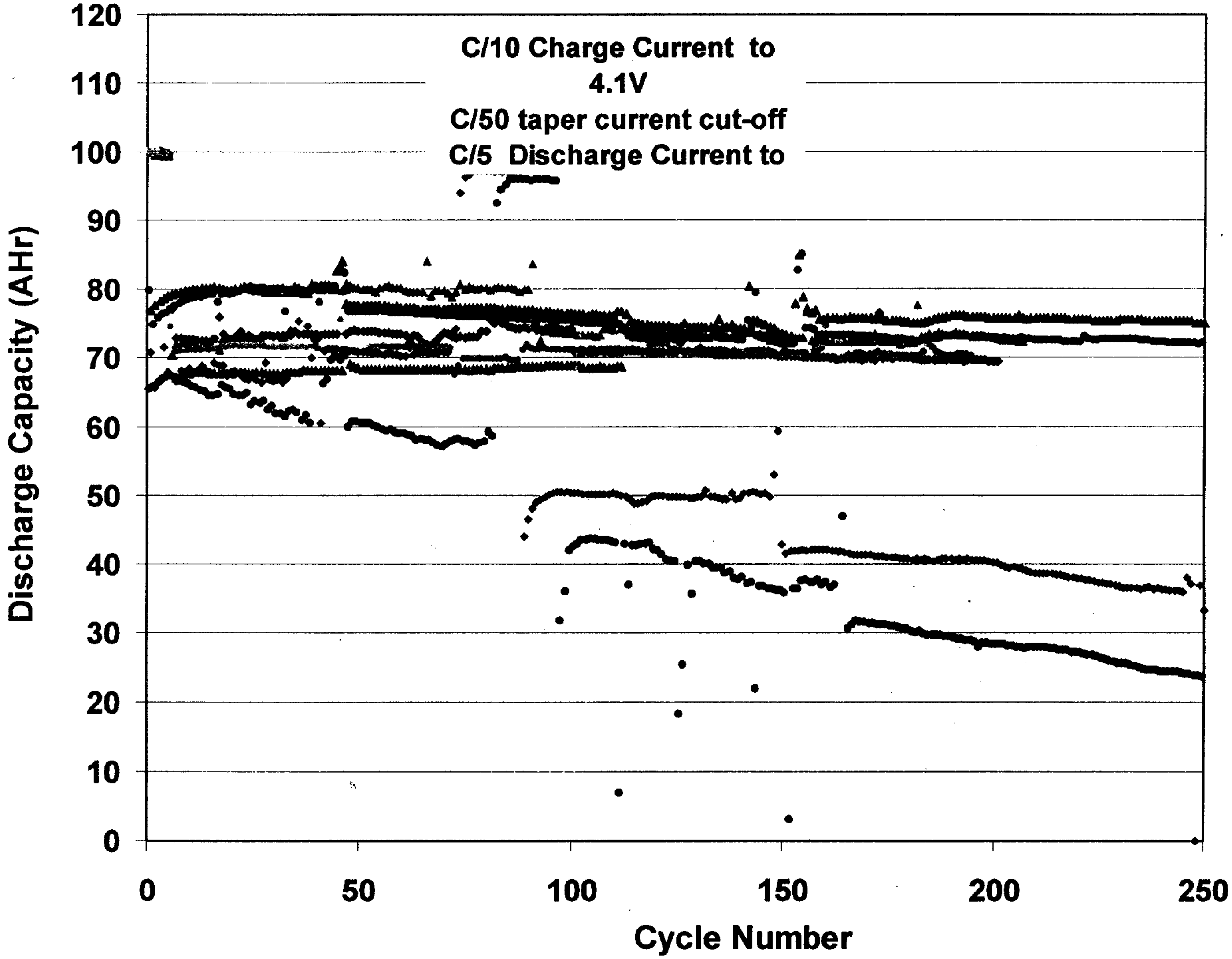
Lithium-Ion Cells for 2003 MSR Athena Rover

Room Temperature Cycle Life Performance
Comparison of Different Cell Designs and Sizes

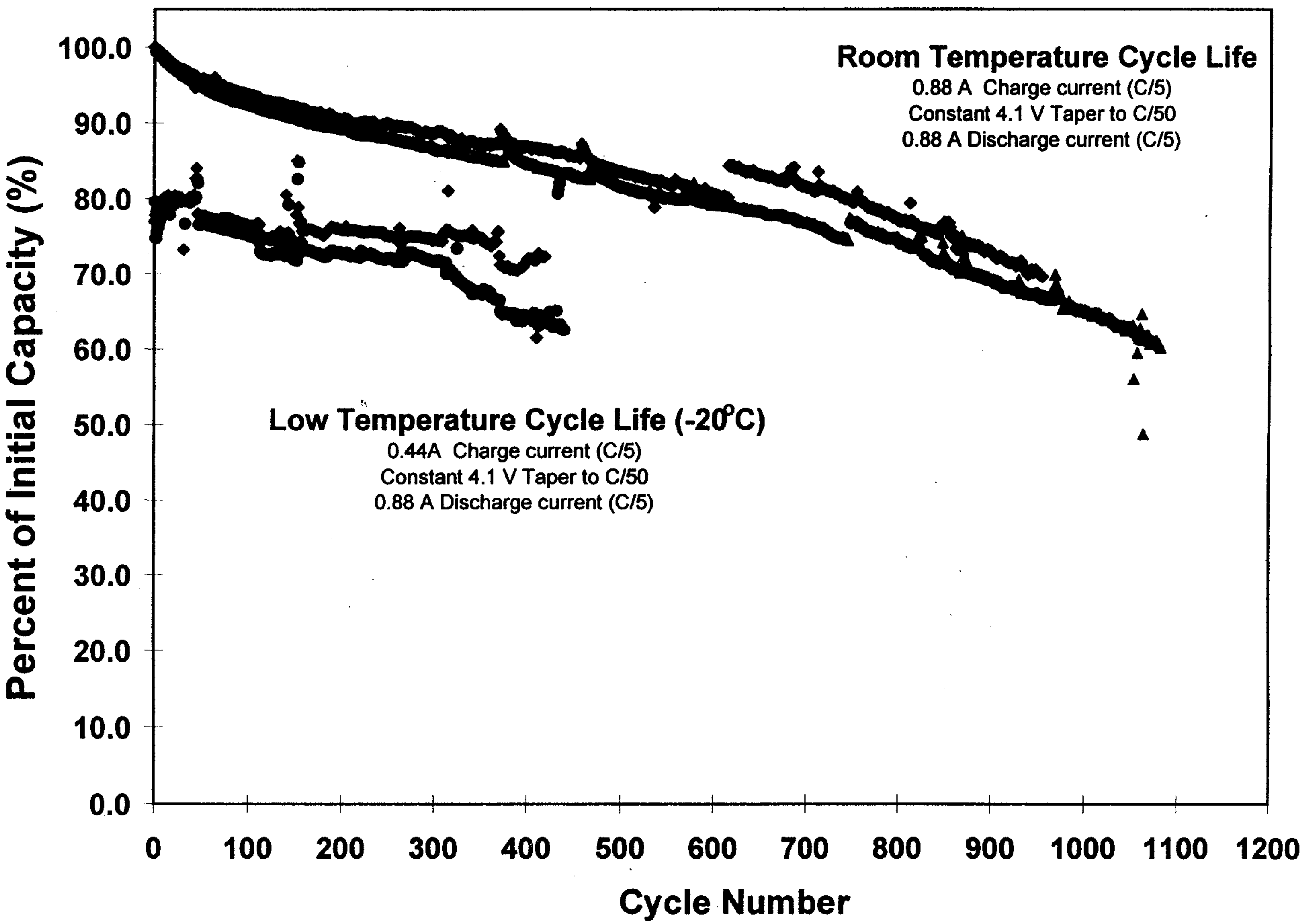


Lithium-Ion Cells for 2003 MSR Athena Rover

Comparison of Cycling at -20°C

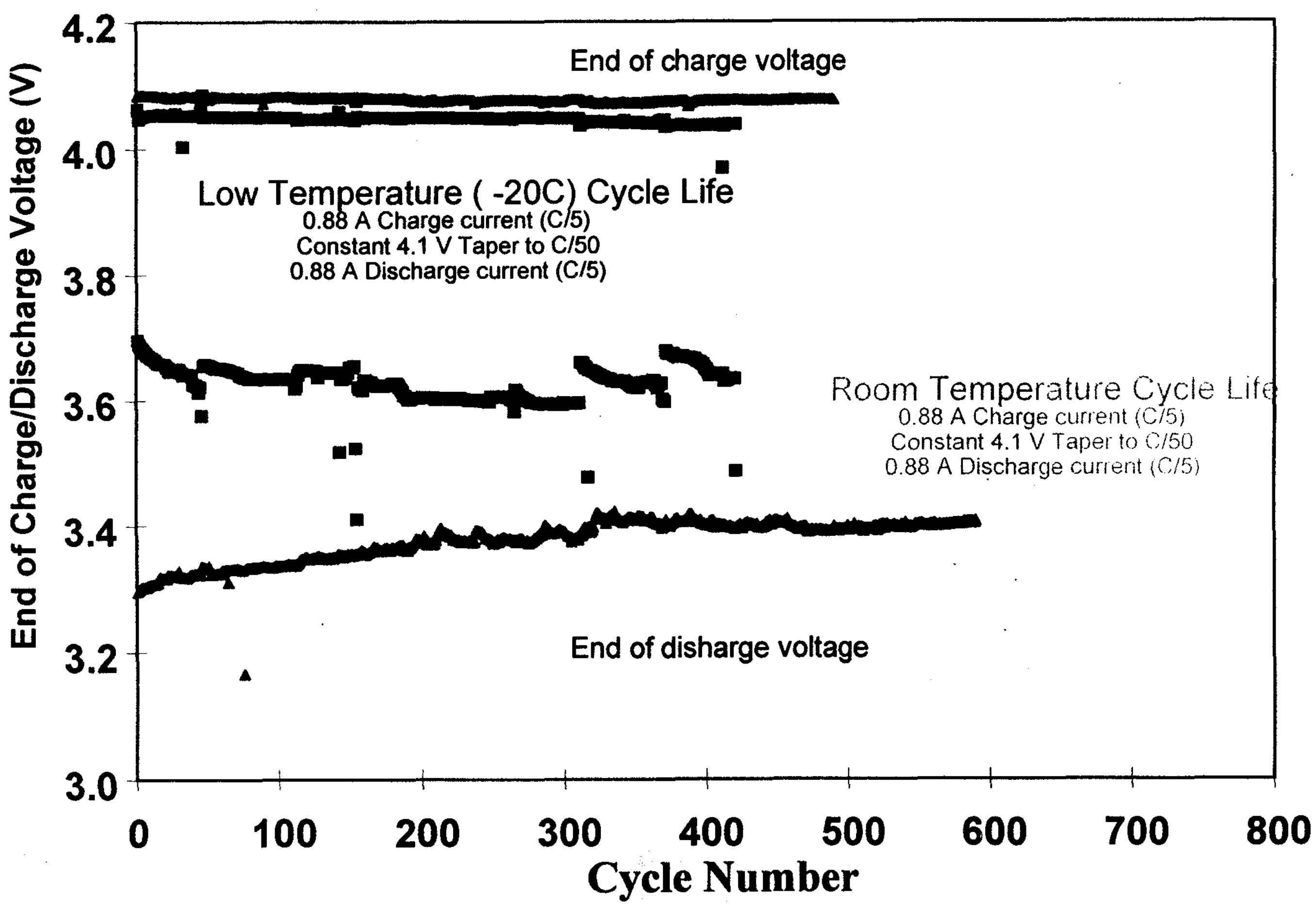


D-Size Lithium-Ion Cells
Cycle Life at Different Temperatures

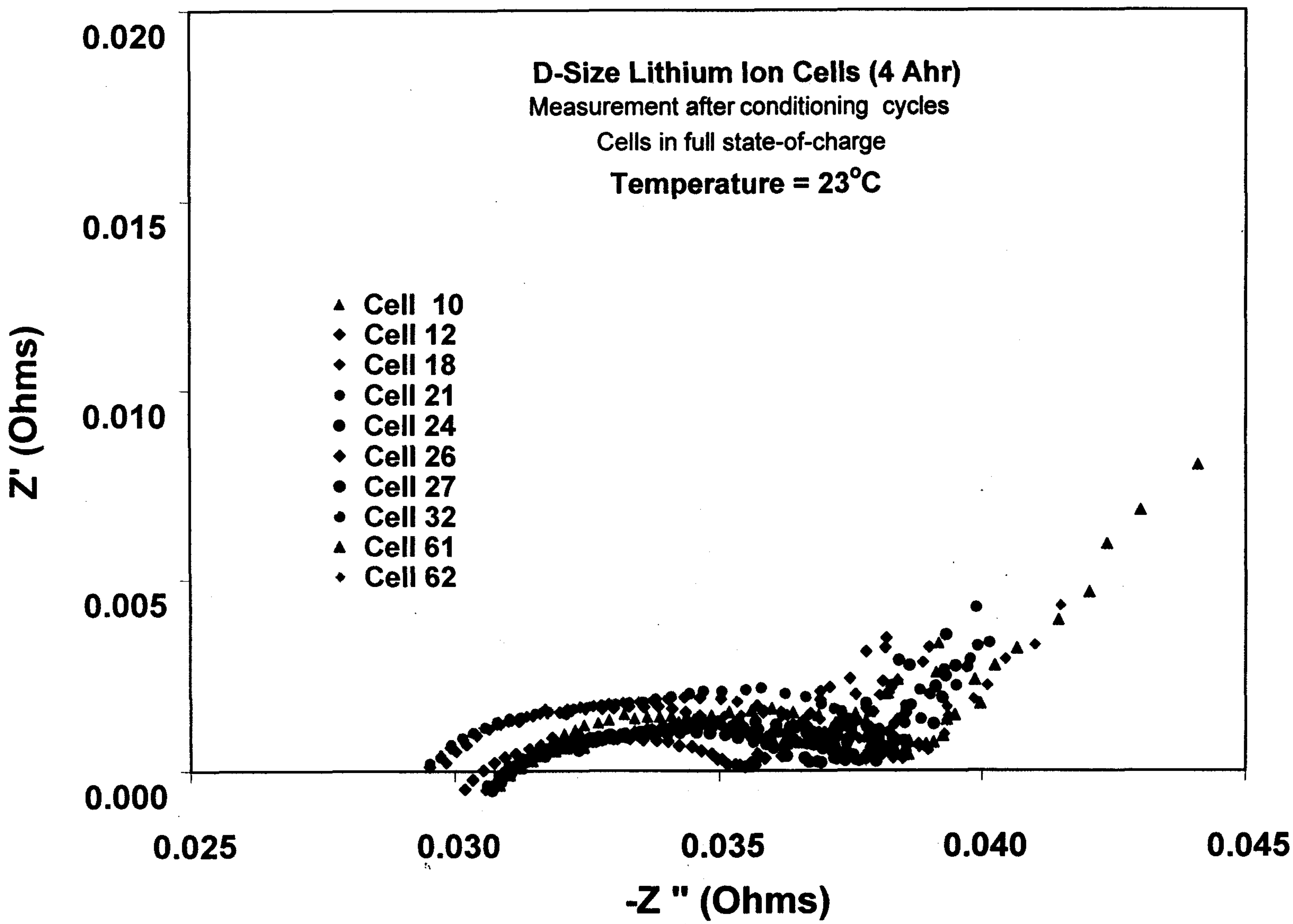


D-Size Lithium-Ion Cells

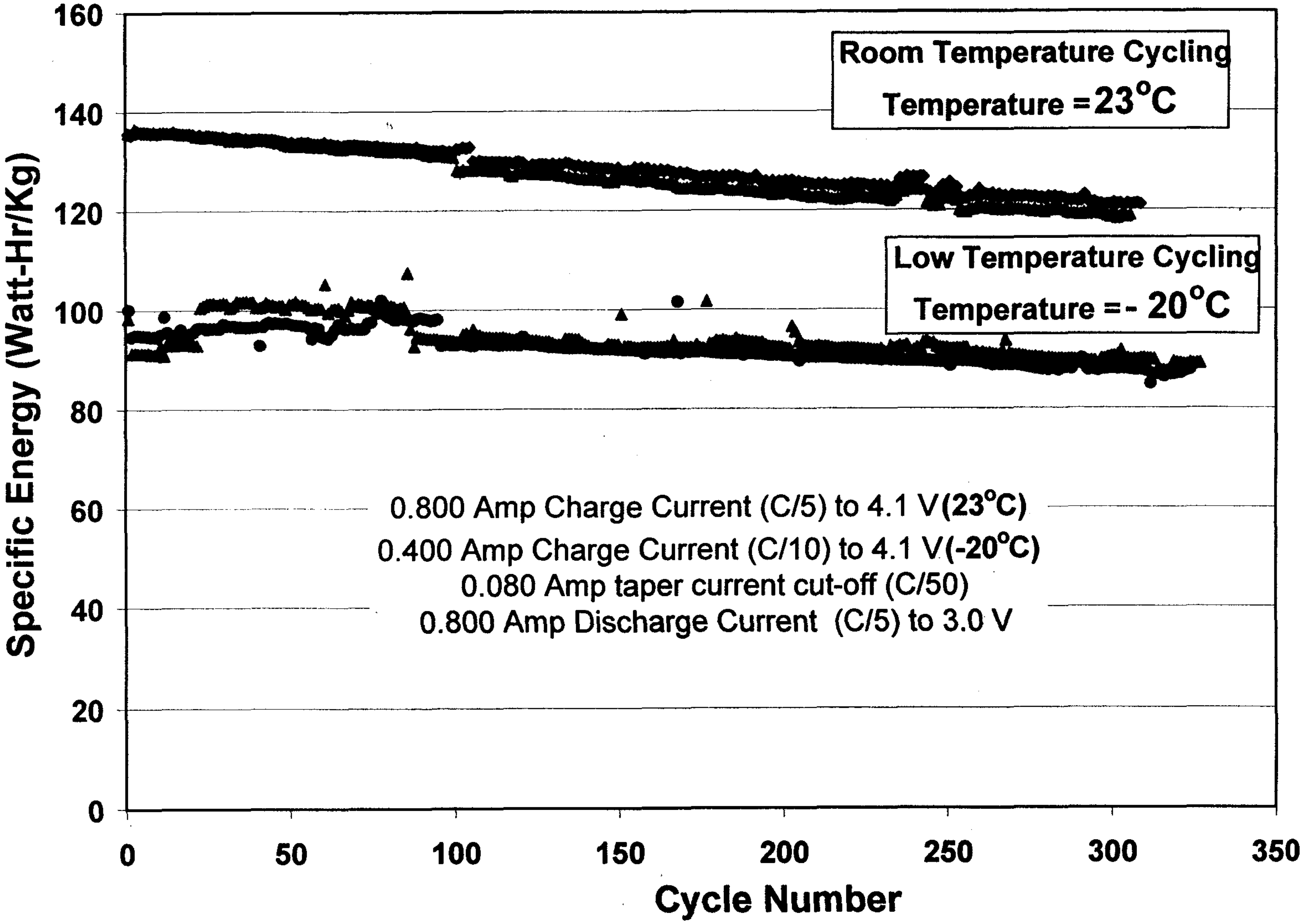
Cell Voltage at the End of Charge and Discharge During Cycling



Lithium-Ion Cells (D-Size)
AC Impedance After Conditioning Cycles



D-Size Lithium-Ion Cells
Cycle Life at Different Temperatures



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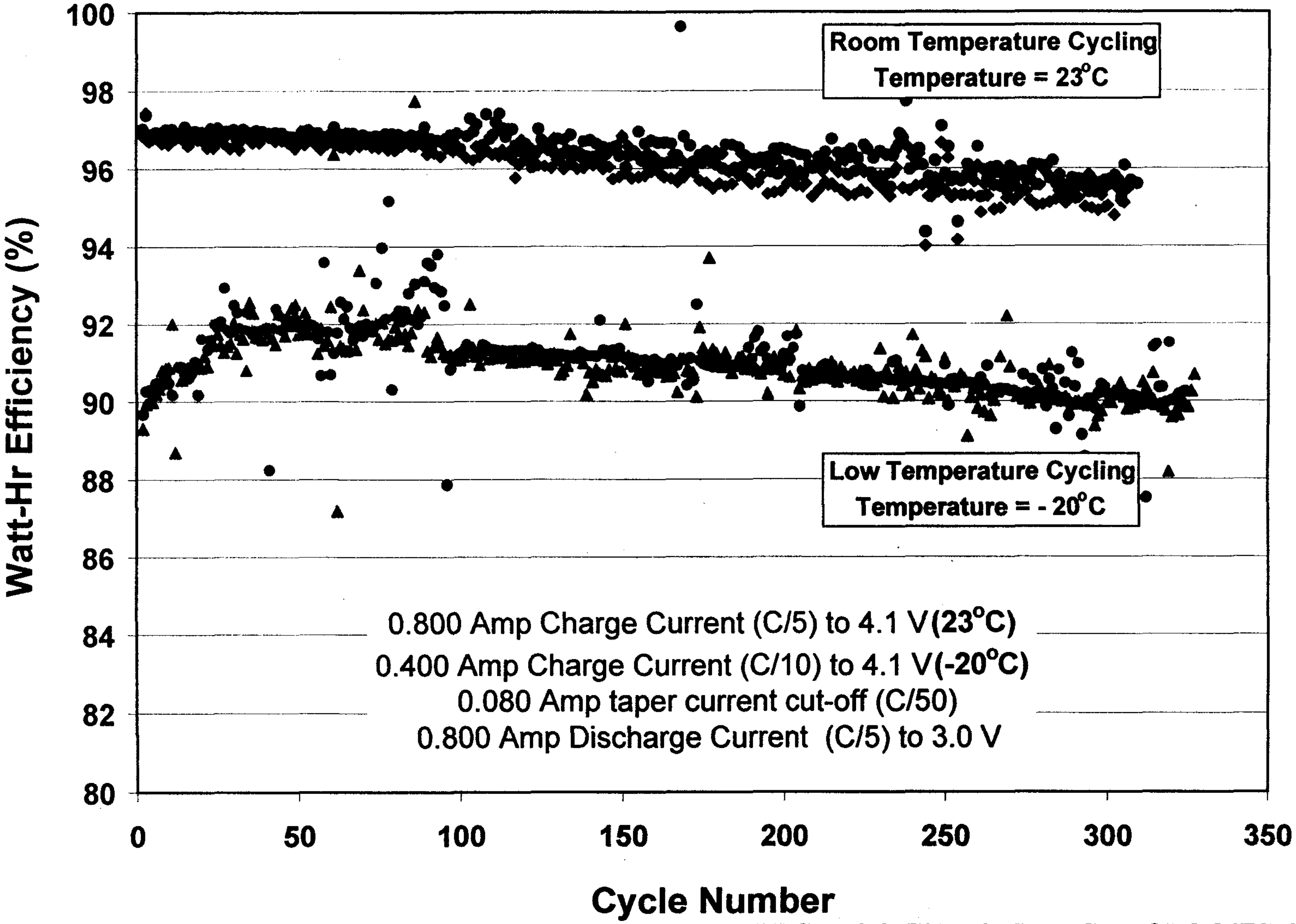
D-Size Lithium-Ion Cells
Energy Efficiency During Cycling



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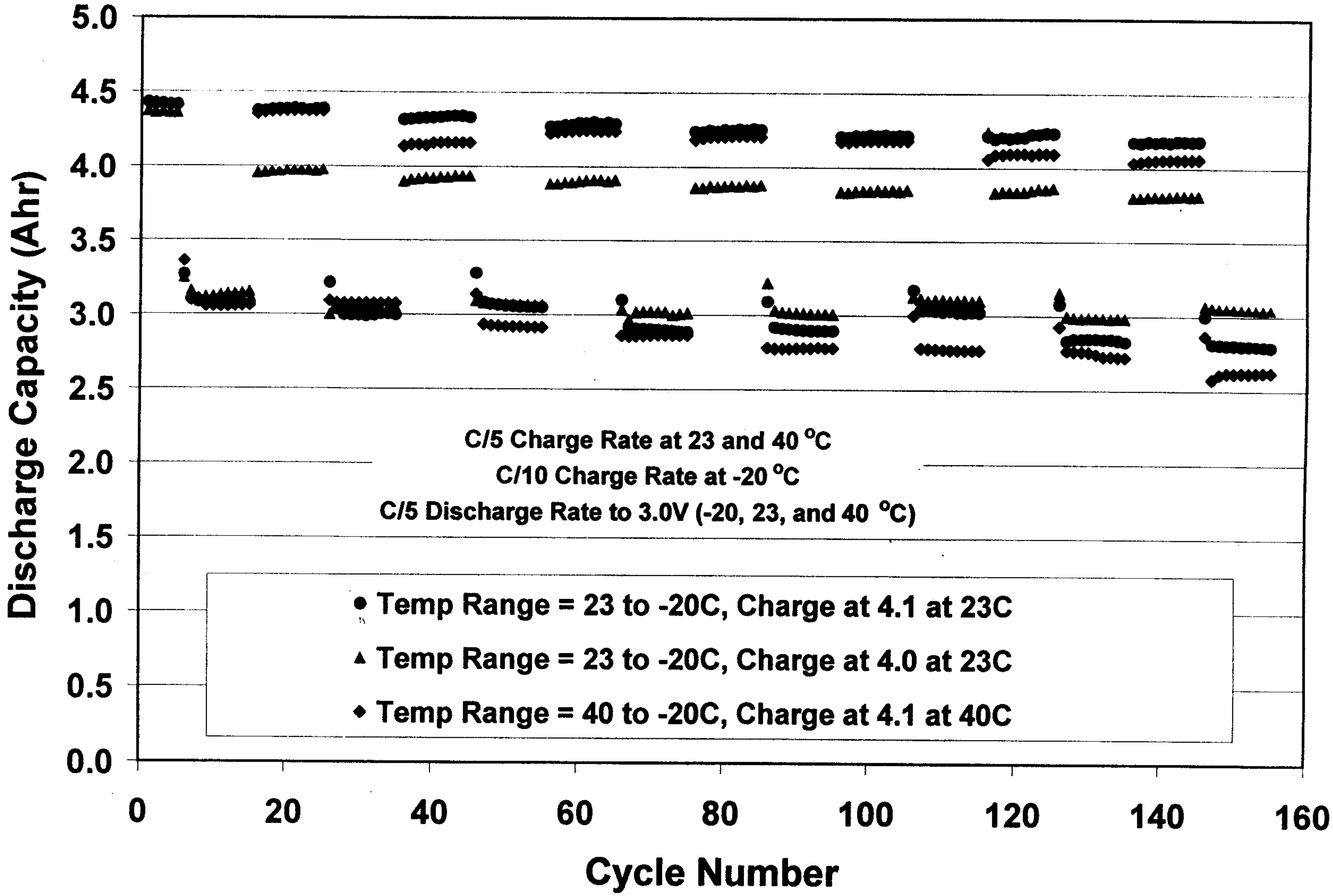
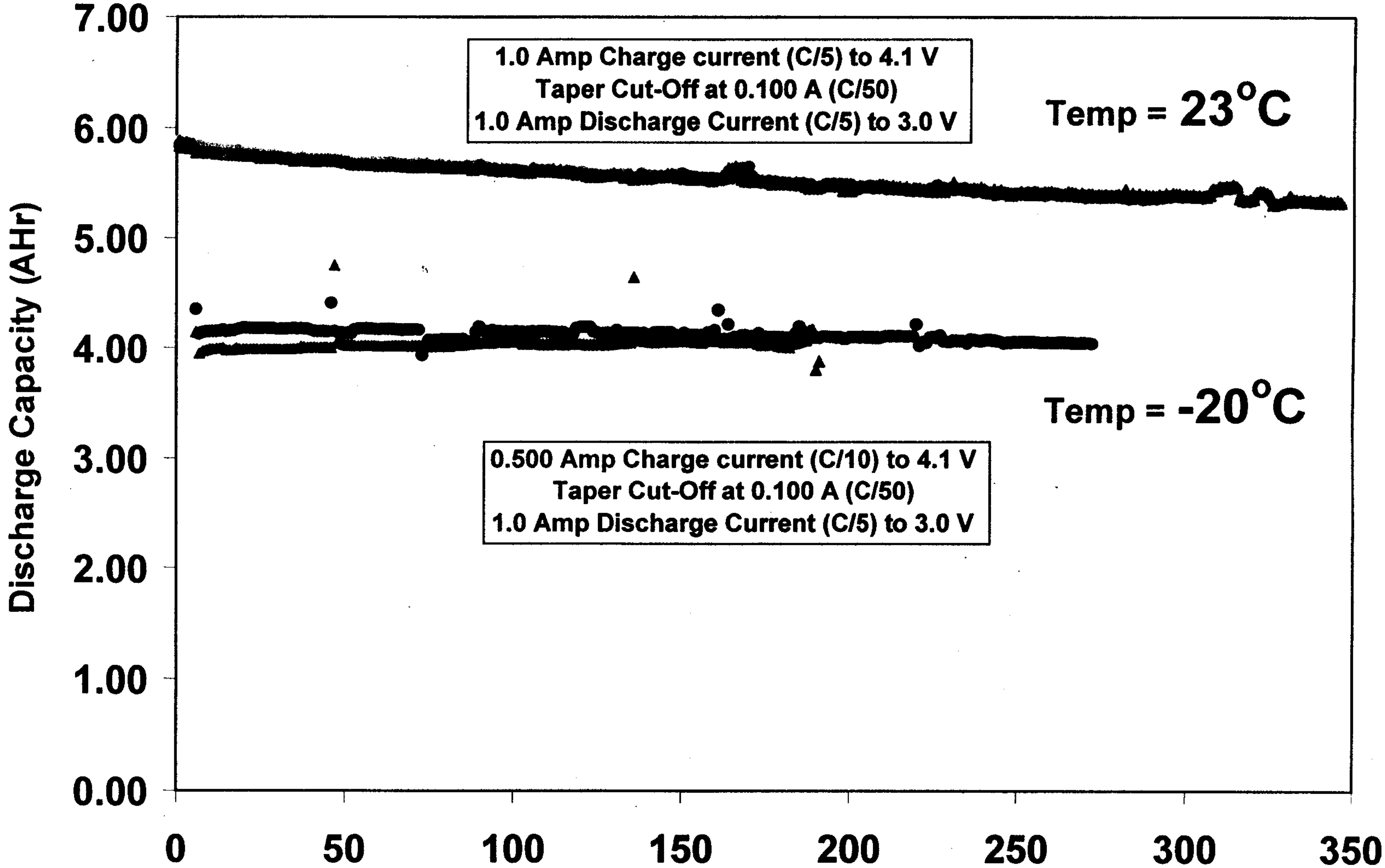
D-Size Lithium-Ion Cells for Mars Rover Applications Variable Temperature Cycling Tests



Lithium-Ion Cells
Cycle Life at Different Temperatures



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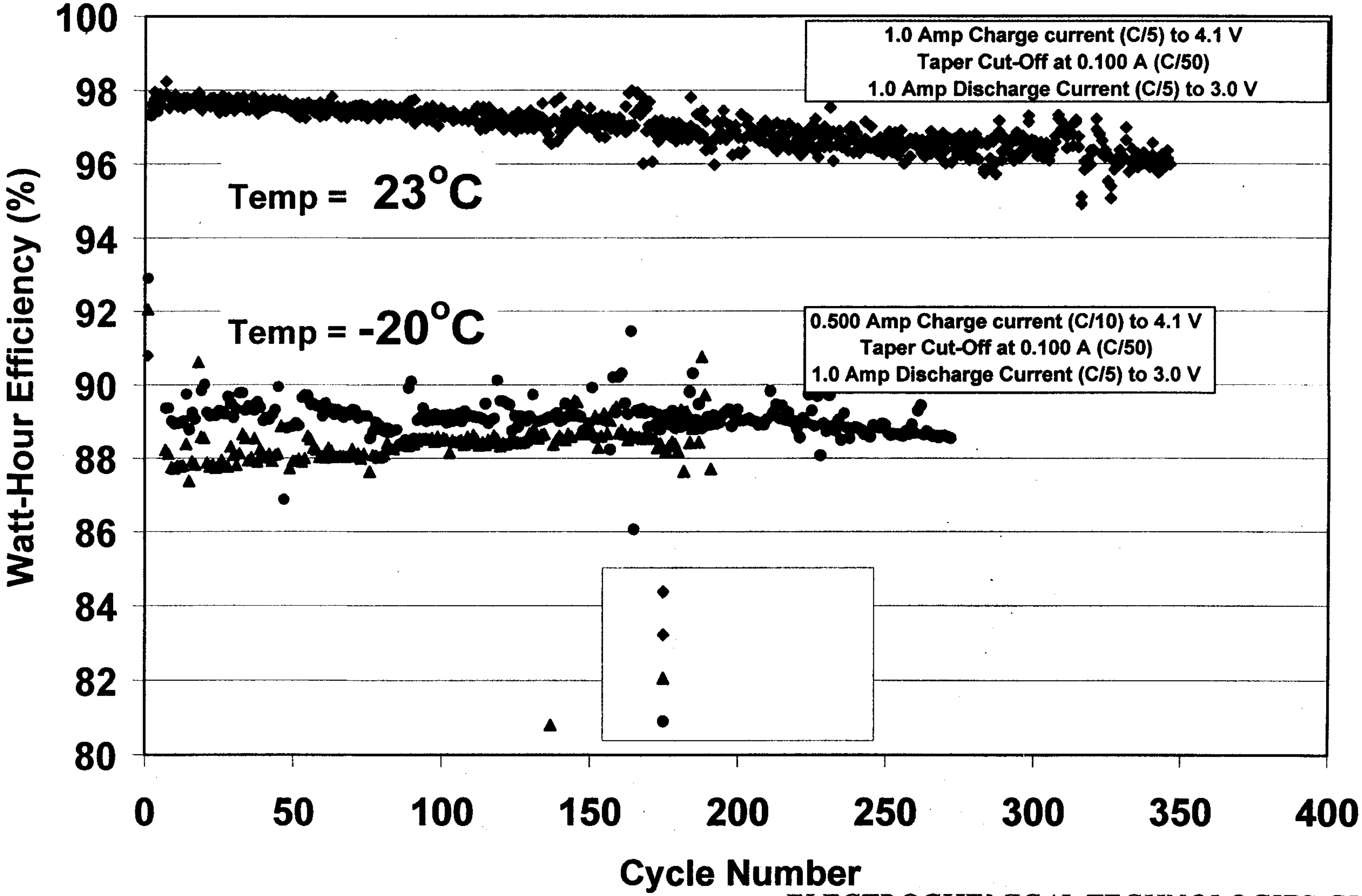
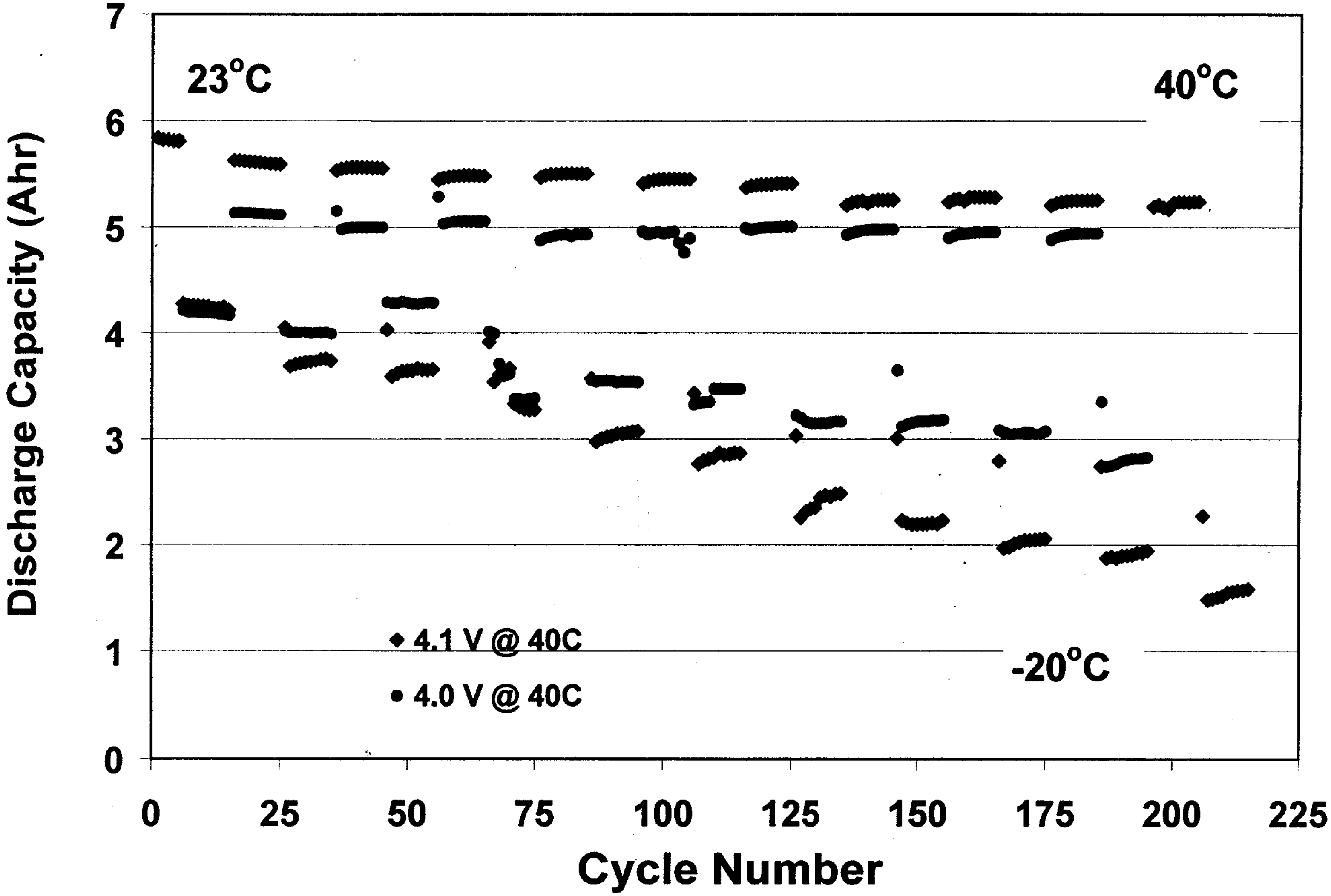
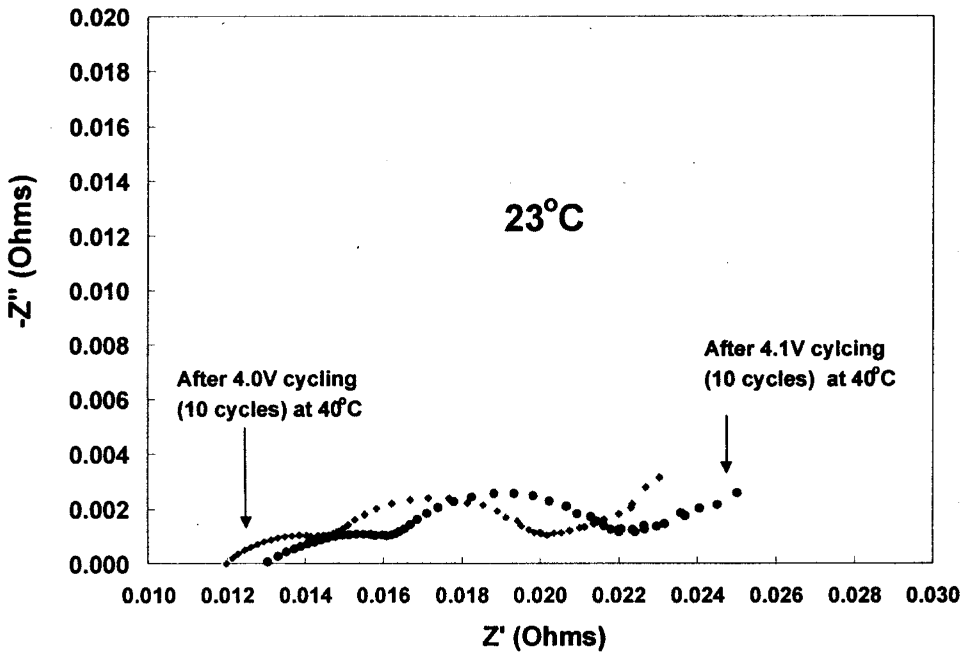
Lithium-Ion Cells
Energy Efficiency During Cycling

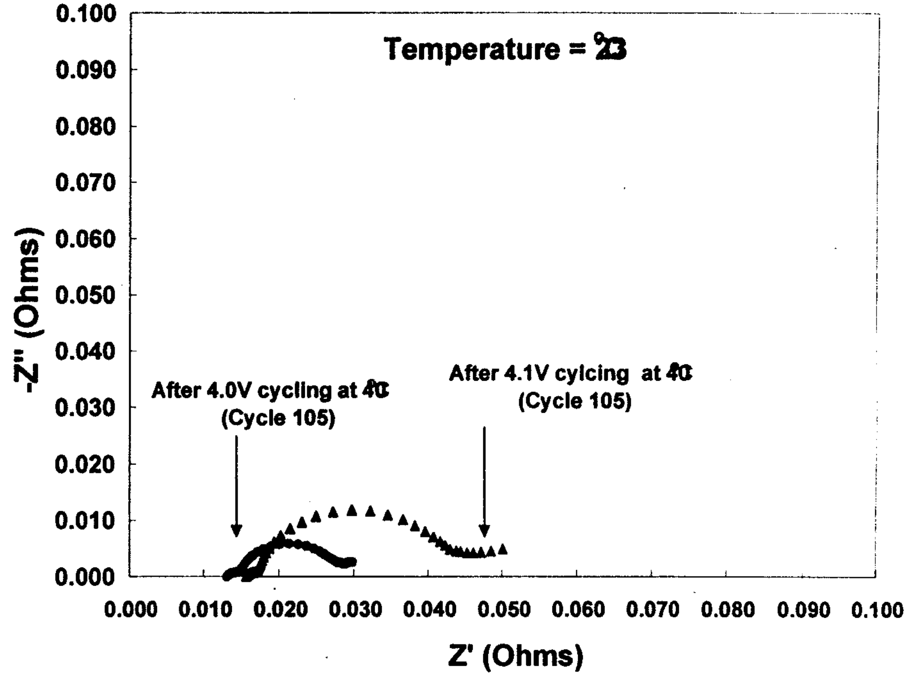


Lithium-Ion Cells
Variable Temperature Cycling Results



Lithium-Ion Cells
Variable Temperature Cycling: EIS Measurements





Rate Characterization Tests

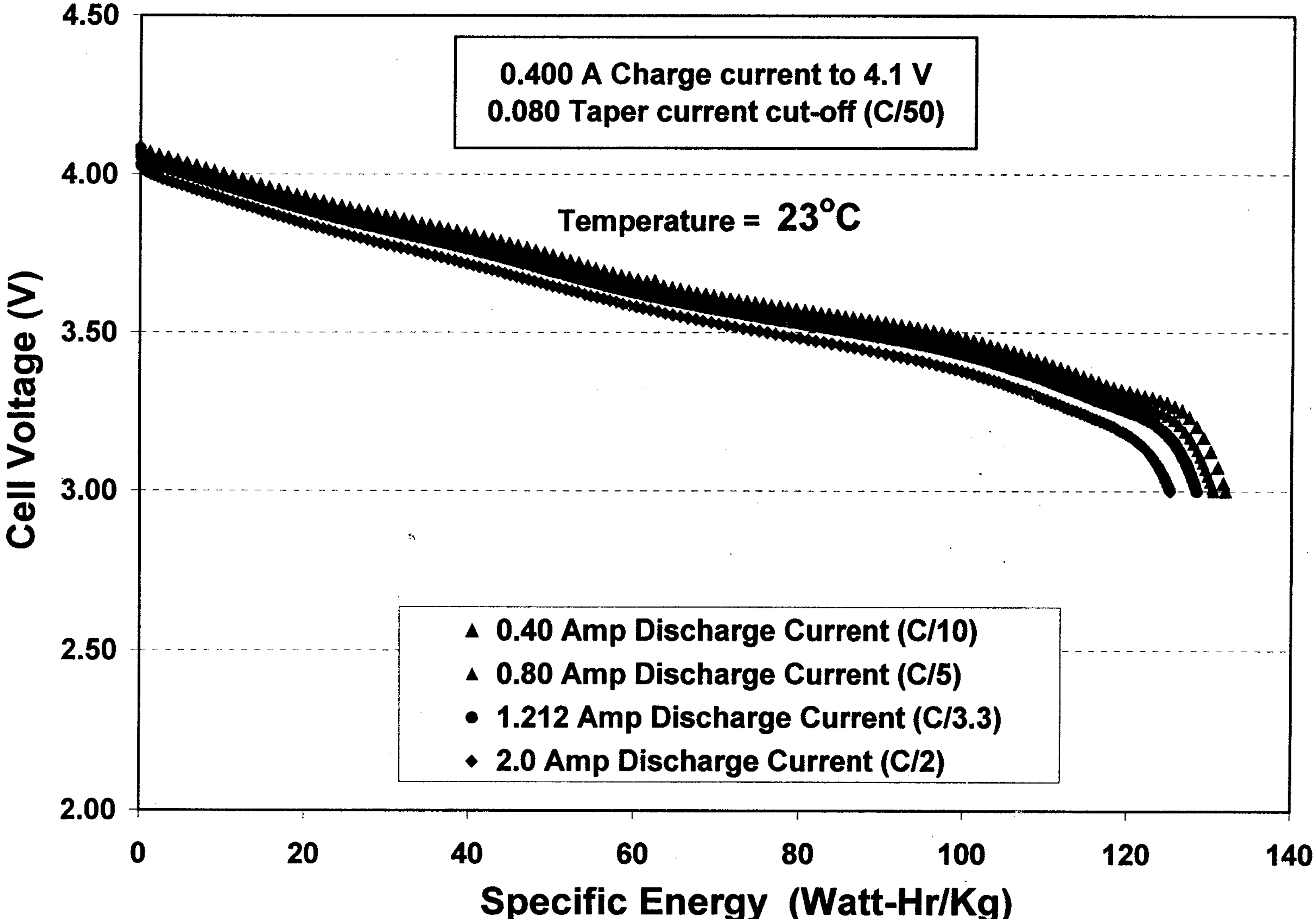
Approach:

- Range of charge and discharge rates (C/2, C/3.3, C/5 and C/10)
- Range of temperatures investigated (-20, 0, 23, 40°C)
- Pulse capability (40 and 60A)

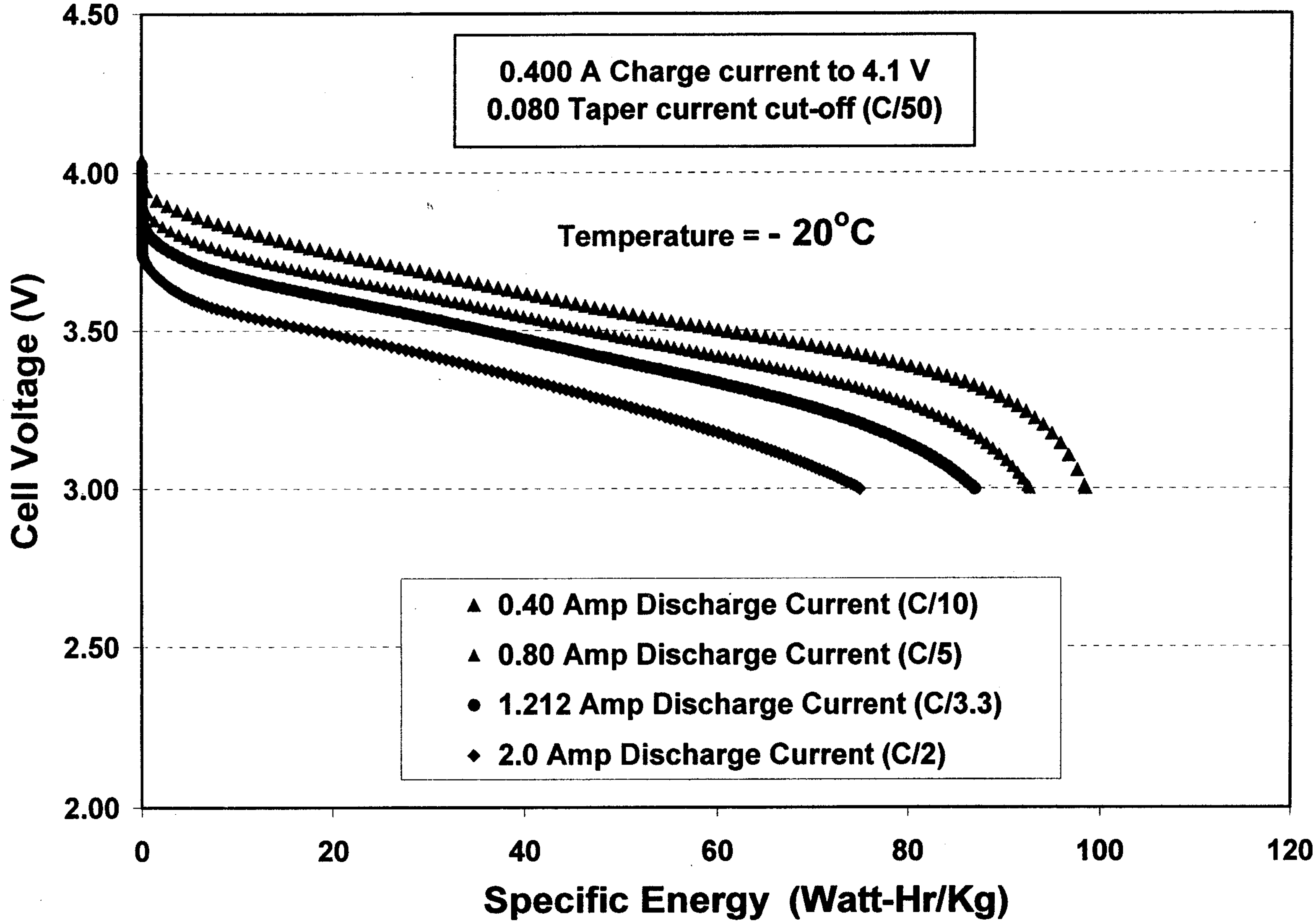
Cell Performance Aspects

- Discharge/charge capacity (Ah)
- Discharge energy (Wh/Kg)
- Watt-hour efficiency (round-trip efficiency)
- Heat generation
- Effect of cell history upon rate capability

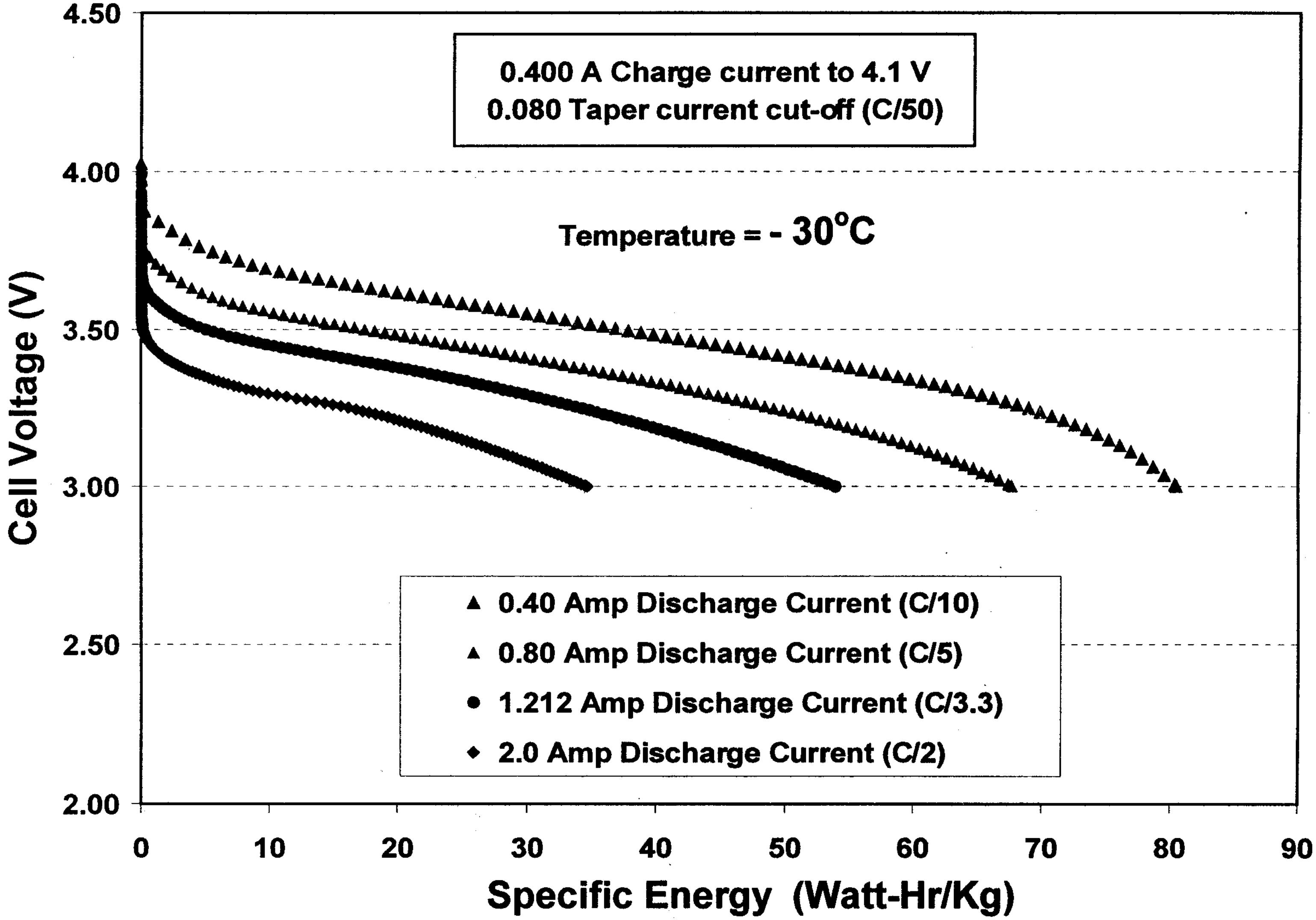
Lithium-Ion Cells (D-Size)
Specific Energy at Room Temperature



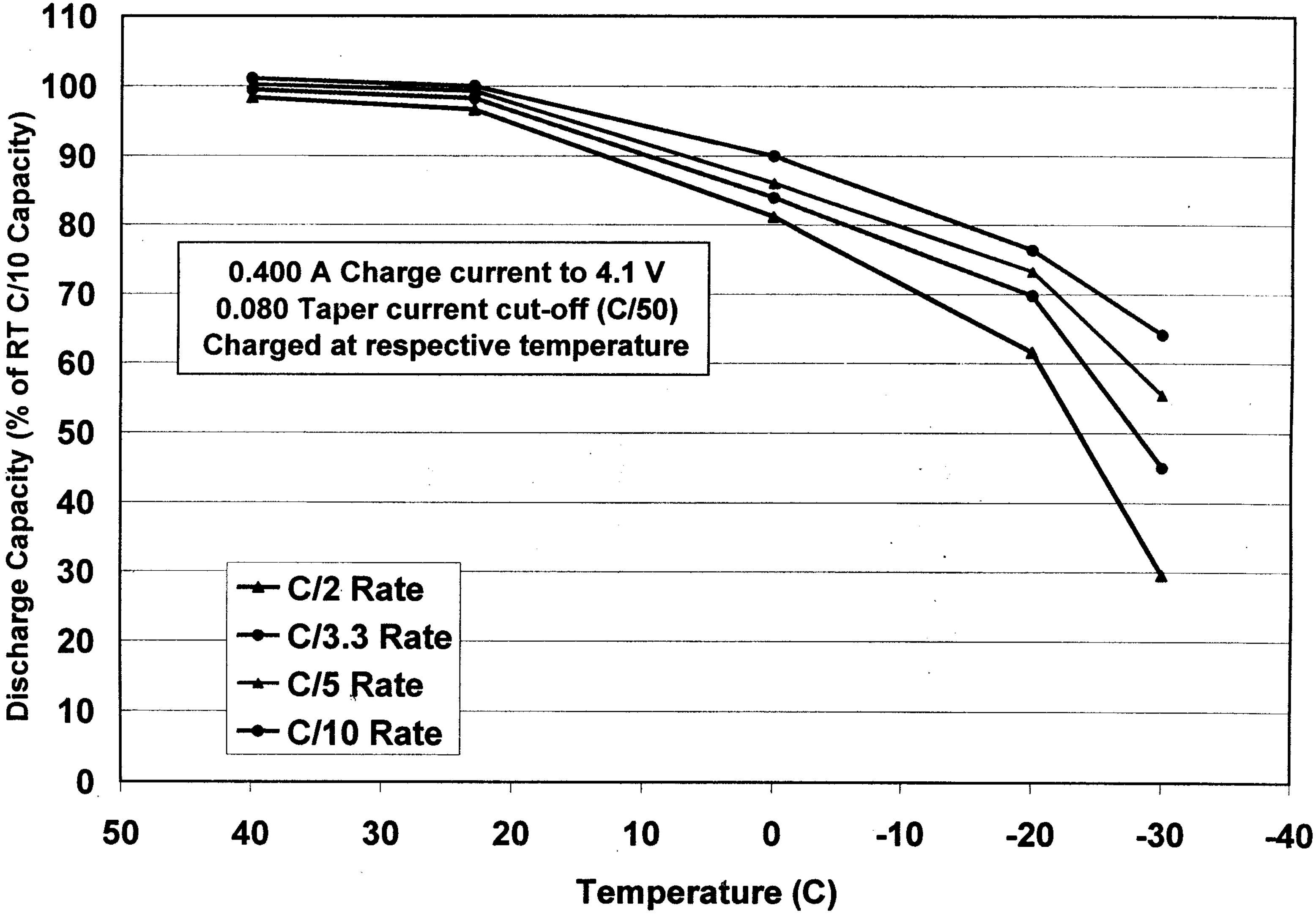
Lithium-Ion Cells (D-Size)
Discharge Characteristics at Low Temperature (-20°C)



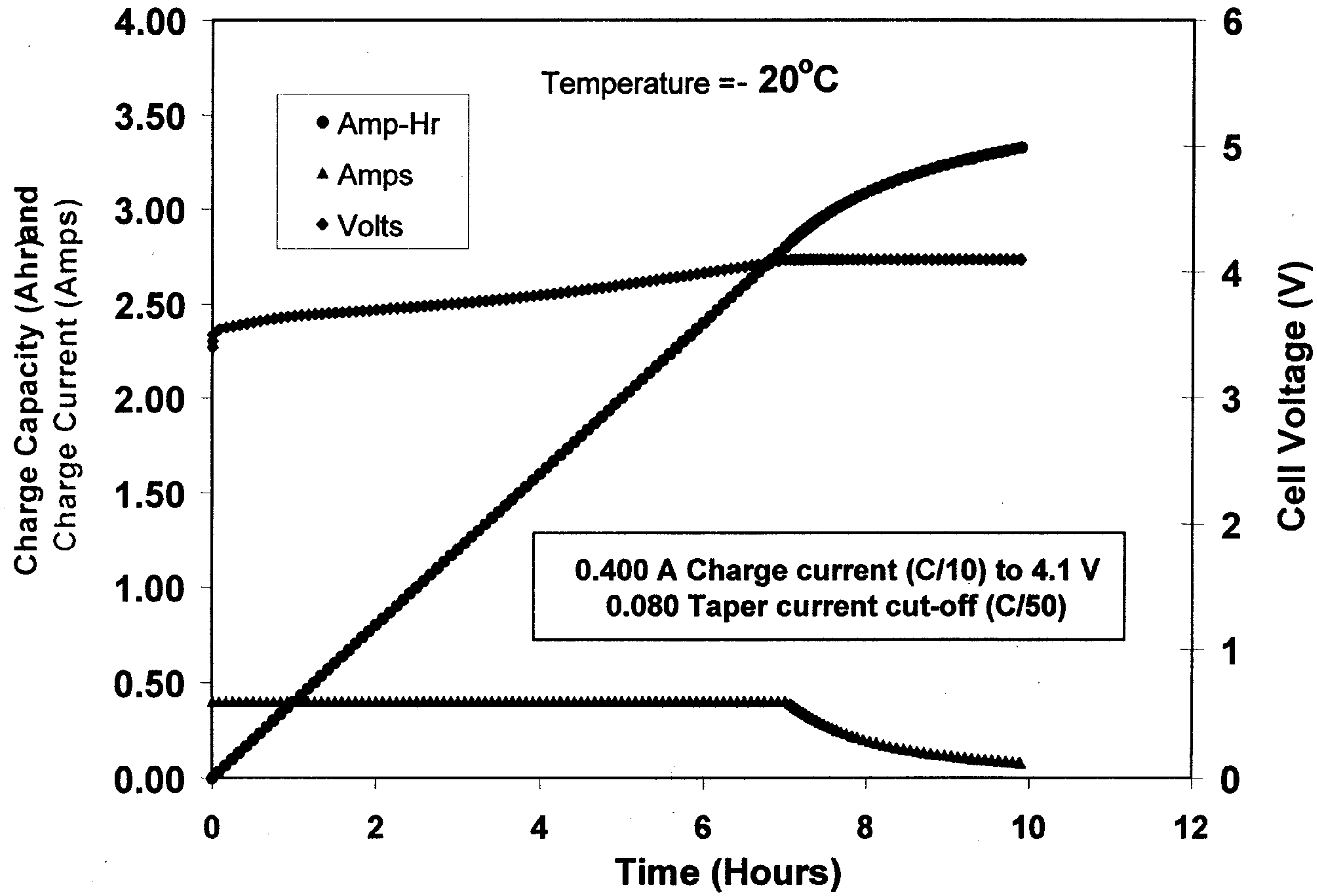
Lithium-Ion Cells (D-Size)
Discharge Characteristics at Low Temperature (-30°C)



Lithium-Ion Cells (D-Size)
Discharge Behavior as a Function of Temperature



Lithium-Ion Cells (D-Size)
Charge Characteristics at Low Temperature (-20°C)



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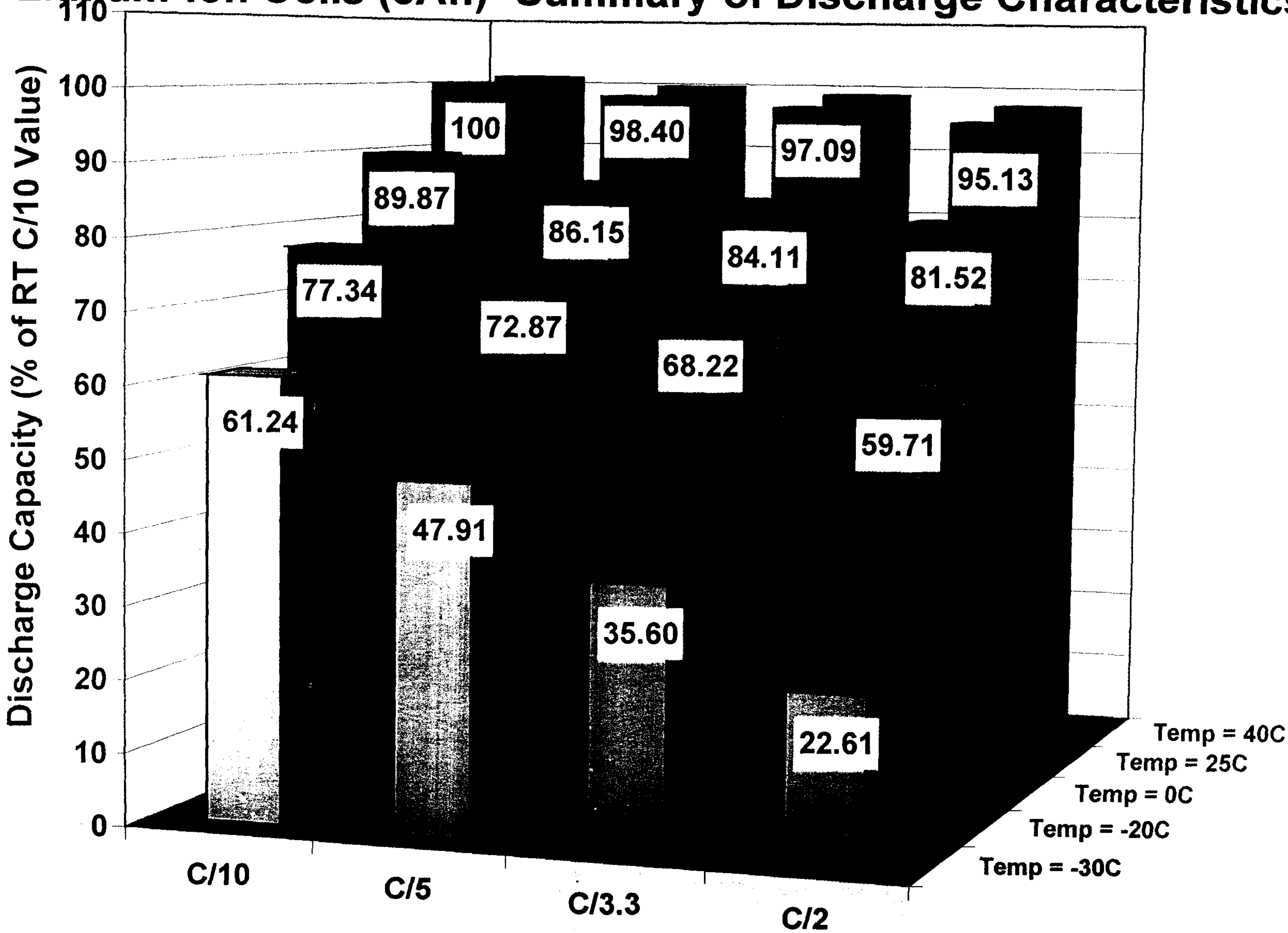
Lithium-Ion Cells (5Ah)- Summary of Discharge Characteristics

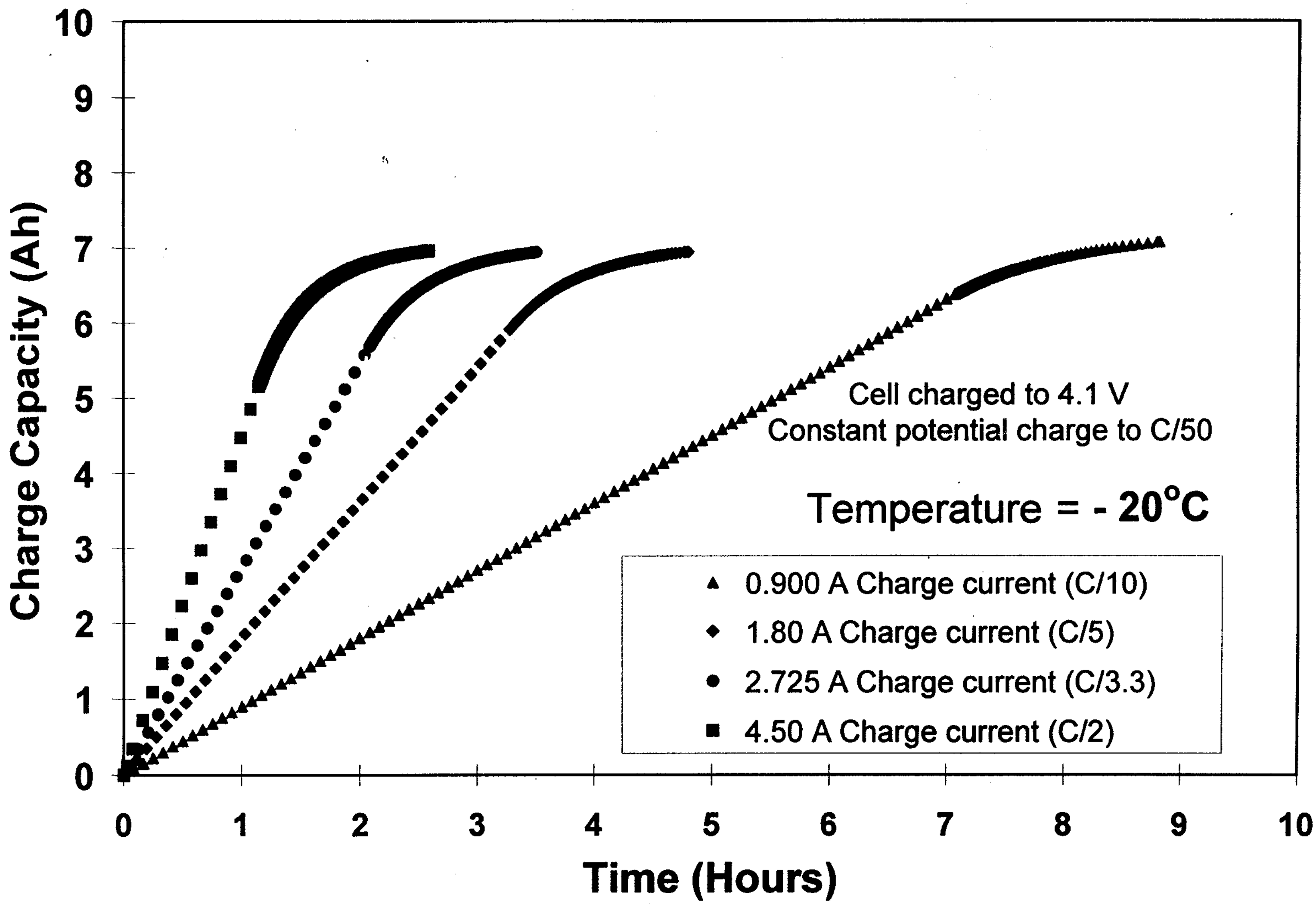


Lithium-Ion Cells for 2003 MSR Athena Rover

Charge Characteristics

- Charge acceptance at various rates and temperatures
- Effect of cycle life upon charge characteristics
- Effect of charge voltage upon cell performance
    - V/T characterization
- Effect of charge methodology

Lithium-Ion Cells
Charge Characteristics at Low Temperatures



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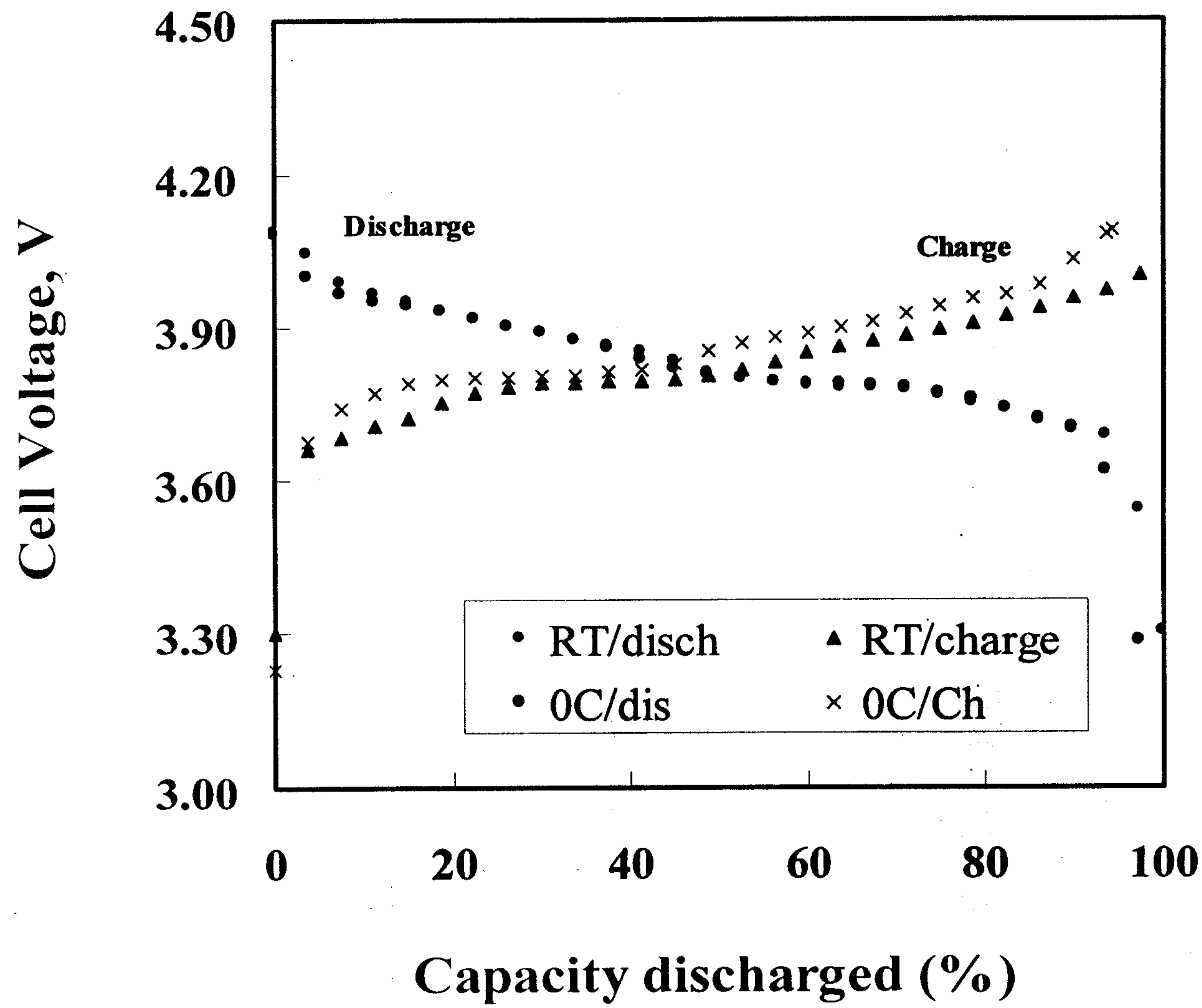
Titration Curve of Li IonCell



Lithium-Ion Cells for 2003 MSR Athena Rover

Capacity Retention Characterization Tests

Approach:

- Identify optimum storage conditions
- Quantify performance degradation due to storage
    - 2 Month storage test (0 and 40°C, 50 and 100% SOC)
    - 10 Month storage test (0 and 40°C, 50 and 100% SOC)

Performance Evaluation Criteria:

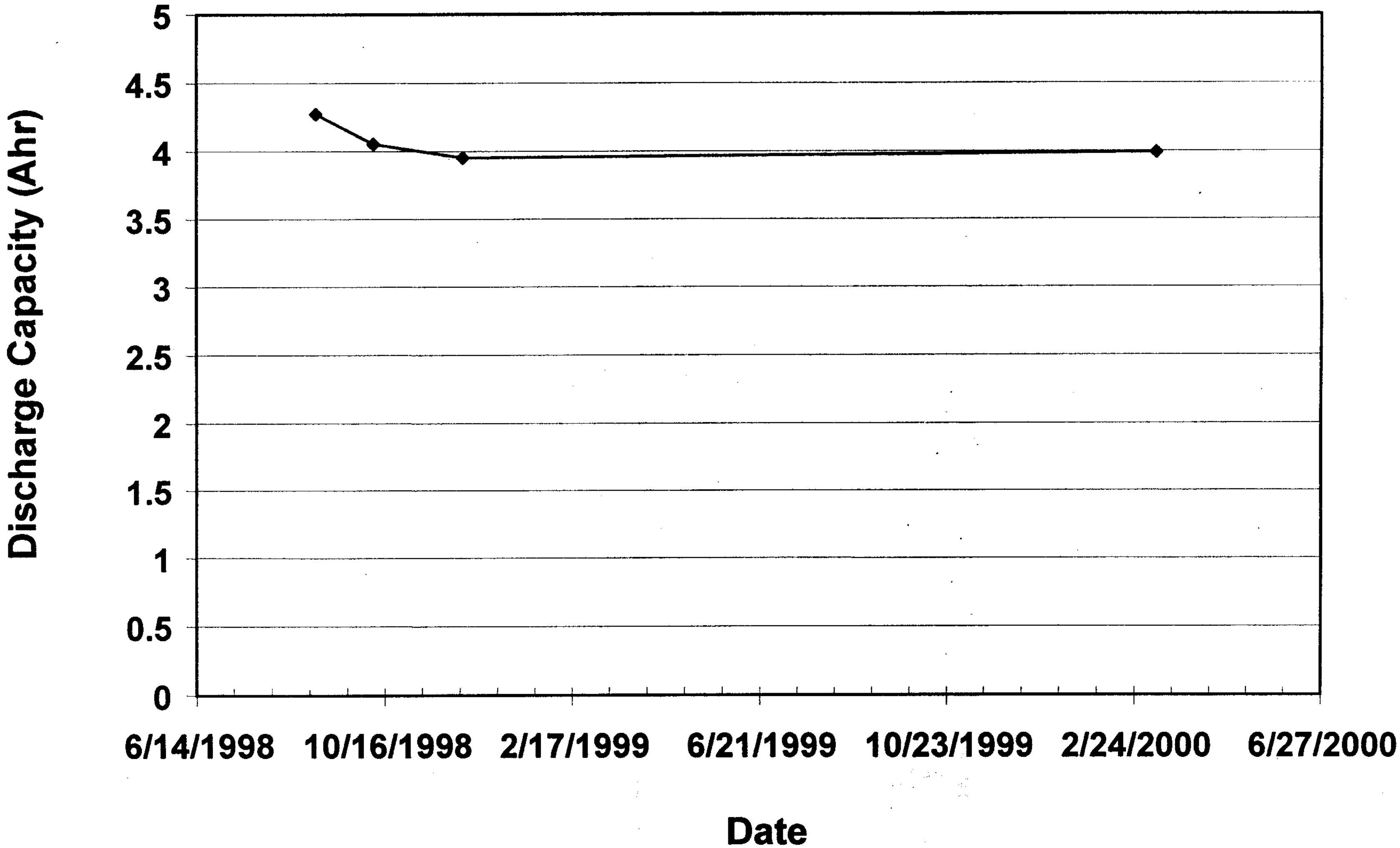
- Permanent loss of reversible capacity
- Self-Discharge of stored capacity
- Impact upon low temperature performance

Lithium-Ion Cells for 2003 MSR Athena Rover

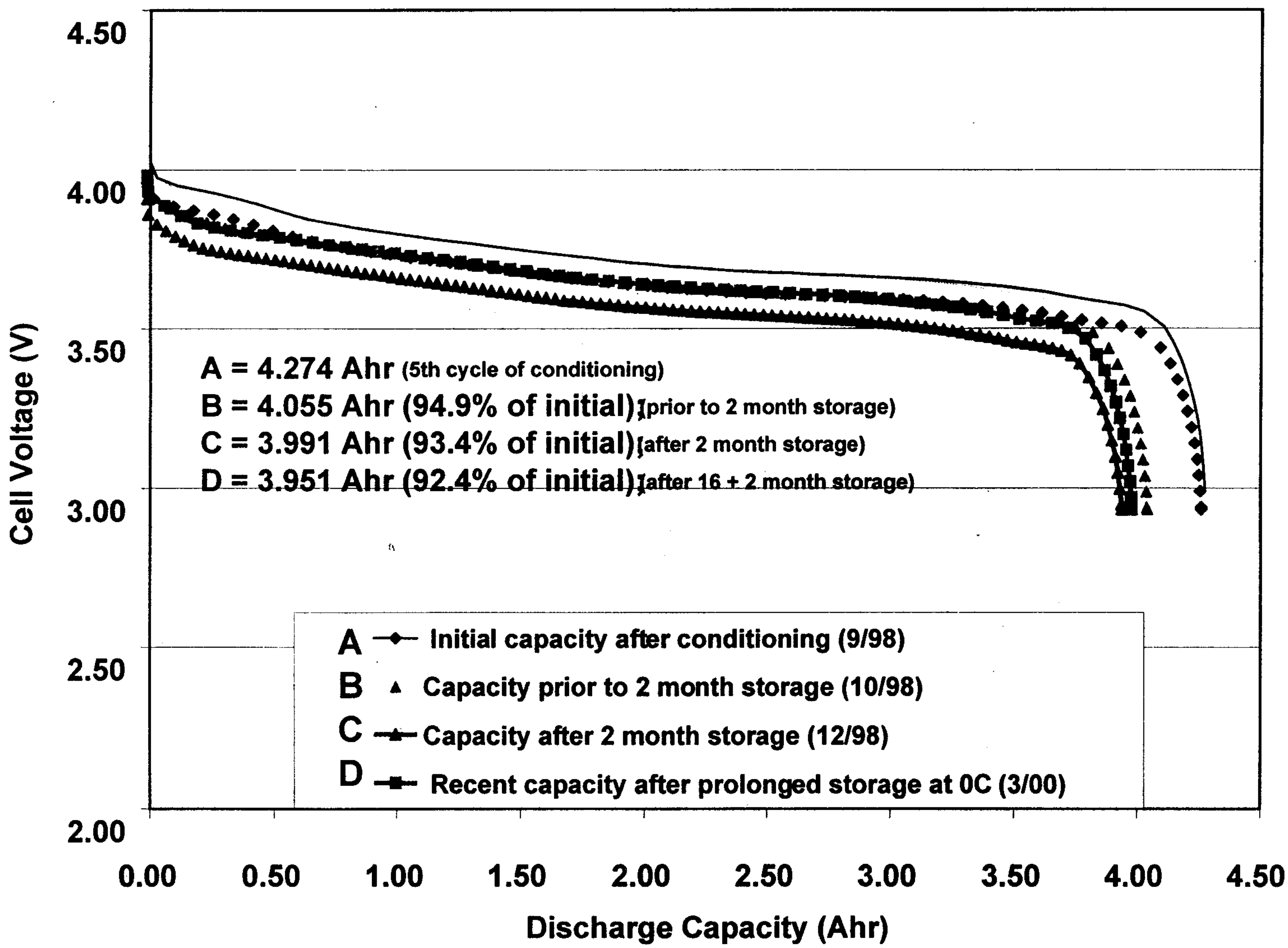
Storage Characteristics 2 Month Storage Test

State of Charge	Temperature of Storage	Storage Time (Months)	Reversible Capacity (%)	Stored Capacity Loss (%)
50%	0°C	2	99.9	0.4
100%	0°C	2	97.5	7.88
50%	40°C	2	97.3	13
100%	40°C	2	92.9	13.3

Capacity of Li ion Cells During storage



Li Ion D cell Storage Characteristics



SUMMARY

- **Lithium ion cells of capacity 4-9 Ah, fabricated in U.S and tested for 2003 Mars Rover mission at JPL under the NASA-DoD joint effort have shown**
  - **High specific energies of $\geq$ 120 Wh/kg**
  - **Excellent cycling characteristics at RT and LT**
  - **Improved low temperature performance and**
  - **Good storage characteristics during cruise**
- **Low temperature performance after frequent exposure to high temperatures is affected more significantly than during continuous cycling at low temperature and is dependent on charge voltage.**

Acknowledgments

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